Ageing, Gait

and

Falls Risk

By

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

University of Tasmania (October, 2010)

Declaration of originality

The thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis.

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Statement of Co-authorship

This thesis includes papers for which Michele Callisaya (MC) is not sole author. MC took the lead in this research in that she designed the research, undertook fieldwork, analysed the data and wrote the manuscripts. She was, however, assisted by the co-authors. The contributions of each author are detailed below.

1. The paper reported in chapter 4:

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The contribution of each author:

MC contributed to the design of the study, acquisition of data, data management, with LB undertook all data analyses and contributed to data interpretation, composed the drafts of the manuscript, and coordinated revision of the manuscript.

LB with MC undertook all data analyses and contributed to data interpretation, provided statistical expertise, and revised the manuscript.

MS contributed to interpretation of the data and revising the manuscript.

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VS was responsible for obtaining approvals for the study, design and conduct of the study, interpretation of the data and revising the manuscript.

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LB with MC and ABT undertook all data analyses and contributed to data interpretation, provided statistical expertise, and revised the manuscript.

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The contribution of each author:

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Abstract

Mobility impairments are extremely common in older age, often resulting in loss of independence, reduced social participation and injuries from falls. As well as reduced quality of life, these outcomes produce significant medical and residential care costs for the individual and for society. With the rapid ageing of populations, there is an urgent need to identify risk factors to prevent mobility decline and associated problems.

This thesis aims to examine associations between age and walking performance, their relationships to the sensorimotor factors that may contribute to walking impairments, and finally to identify measures of walking performance that increase the risk of falling.

In studies of population-based samples of community dwelling older adults (60-86 years), greater age was associated with poorer performance in gait speed, step length, double support phase and step width among persons of each sex, and additionally with slower cadence among women. Among men the associations were linear. For women, stronger associations were found among those of greater age. Gait variability measures (the fluctuation in a gait measure from one step to the next) were also examined. Apart from step time variability, for which stronger associations were seen for older women, greater variability in gait measures was linearly associated with greater age.

In further studies of the same population, poorer performance on a range of sensorimotor factors was associated with impaired gait speed, step length, cadence, double support phase and step width, and with greater gait variability. Quadriceps strength explained the greatest proportion of variance for the majority of average measures of gait, whereas postural sway measured with eyes closed standing on a foam mat explained the greatest proportion of variance for gait variability. Differences in the pattern of associations between the sensorimotor factors and average measures of gait were seen for men and women.

Information on falls was collected prospectively over a 12 month period. Greater step length variability and double support phase variability were linearly associated with increased risk of multiple falls, whereas gait speed, cadence and step time variability were non-linearly associated with increased risk of multiple falls. None of the gait measures predicted risk of single falls.

In conclusion, this series of related studies add considerably to knowledge about age-related changes in walking, and to understanding of gait measures and sensorimotor factors that may be targeted to prevent walking impairment and loss of independence in older age. Specific gait measures which may be useful in identifying those at risk and used as outcome measures in intervention programs to reduce falls risk, have been identified.

Table of contents

Table of contents x
List of tables xiii
List of figures xv
Acknowledgements xvi
Publications xviii
Publications directly arising from the work described in this thesis xviii
Papers Submitted xviii
Other publications xix
Conference presentations arising from this thesis xix
Awards and grants resulting from thesis material xx
List of abbreviations xxii
Chapter 1: Introduction 1
1.1 An aged and ageing population 1
1.2 Mobility, walking and gait 2
1.3 Falls in older people 11
1.4 Summary 14
1.5 Overview of the investigation reported in this thesis 15
1.6 Structure of this thesis 16
1.7 References 17
Chapter 2: Methods 24
2.1 Preface 24
2.2 The Tasmanian Study of Cognition and Gait 24
2.3 Study population 24
2.4 Study samples 25
2.5 Study factors 25
2.6 Collection of falls data 32
2.7 Data analysis 32
2.8 Ethics 32
2.9 Postscript 32
2.10 References 32
Appendix 2A: Falls study follow-up questionnaire 34
Appendix 2B: Falls calendar 35

Chapter 3: Issues in the measurement of the gait parameters 36
3.1 Preface 36
3.2 Introduction 36
3.3 Methods 38
3.4 Results 41
3.5 Discussion 47
3.6 Postscript 49
3.7 References 50
Chapter 4: Sex modifies the relationship between age and gait - A population-based study of older adults 52
4.1 Preface 52
4.2 Introduction 52
4.3 Methods 53
4.4 Results 55
4.5 Discussion 60
4.6 Postscript 62
4.7 References 63
Appendix 4A: Results for DSP (sec) 67
Appendix 4B: Subject-matter considerations in assessing the fit of a linear regression model 69
Chapter 5: Ageing and gait variability – A population-based study of older people. 79
5.1 Preface 79
5.2 Introduction 79
5.3 Methods 80
5.4 Results 82
5.5 Discussion 88
5.6 Postscript 91
5.7 References 91
Appendix 5A: Characteristics of responders and non-responders 95
Chapter 6: A population-based study of sensorimotor factors affecting gait in older people 96
6.1 Preface 96
6.2 Introduction 96
6.3 Methods 97
6.4 Results 99

6.5 Discussion 102
6.6 Postscript 108
6.7 References 109
Appendix 6A: The pathways that cumulate in gait speed 112
Appendix 6B: Sensorimotor factors did not contribute to the curvilinear relationship between gait speed and advancing age for women 117
Chapter 7: Sensorimotor factors affecting gait variability in older people - A population-based study 120
7.1 Preface 120
7.2 Introduction 120
7.3 Methods 121
7.4 Results 123
7.5 Discussion 128
7.7 Postscript 131
7.8 References 132
Chapter 8: Gait, gait variability and the risk of multiple incident falls in older people - A population-based study 136
8.1 Preface 136
8.2 Introduction 136
8.3 Methods 137
8.4 Results 139
8.5 Discussion 143
8.6 Postscript 145
8.7 References 146
Appendix 8A: Characteristics of the overall sample 150
Chapter 9: Summary 151
9.1 Background and aims of the thesis 151
9.2 Methods 152
9.3 Major findings and implications 152
9.4 Recommendations for future research and needs 158
9.5 Conclusion 159
9.6 References 160

List of tables

		Page
Table 2.1	Reliability of gait measures	27
Table 2.2	Test-retest reliability of sensorimotor measures	31
Table 3.1	Characteristics of the sample	41
Table 3.2	Inter-individual (between-subject) average and standard deviation of each gait measure and each intra-individual (within-subject) gait variability measure for each walking trial separately	43
Table 3.3	Inter-individual (between-subject) mean and standard deviation of each gait measure and each intra-individual (within-subject) gait variability measure for combinations of walking trials	44
Table 3.4	Characteristics of the sample	45
Table 3.5	Mean (SD) values of each gait measure and each intra-individual (within-subject) gait variability measure for the two sessions	46
Table 3.6	Test-retest reliability for each gait measure and each intra-individual (within-subject) gait variability measure	46
Table 4.1	Sample characteristics	55
Table 4.2	Correlations between gait variables in men and women	56
Table 4.3	Univariable associations between age and gait measures	57
Table 4.4	Cross-sectional effect of an additional year of age on gait measures	59
Table 5.1	Sample characteristics	83
Table 5.2	Correlations between subject characteristics and gait variables	84
Table 5.3	Univariable associations between age and gait variability measures	85
Table 5.4	Multivariable regression – cross sectional effect of an additional year of age on gait variability measures	87
Table 6.1	Characteristics of the sample	100
Table 6.2	Age-adjusted partial correlations between sensorimotor and gait variables	101
Table 6.3	Multivariable associations between sensorimotor and gait variables	103
Table 6.4	Partial R^2 values for the regression of gait variables on sensorimotor variables	105
Table 7.1	Sample characteristics	124
Table 7.2	Spearman correlations between sensorimotor and gait variables	125
Table 7.3	Associations between gait variability (outcome) and sensorimotor factors adjusted for covariates	126

Table 7.4	Multivariable associations between gait variability (outcome) and sensorimotor factors	128
Table 8.1	Sample characteristics	140
Table 8.2	Adjusted association of average measures of gait with single and multiple falls	141
Table 8.3	Adjusted association of gait variability measures and single and multiple falls	142

List of figures

		Page
Figure 1.1	Population projections Australia 2006-2056.	2
Figure 1.2	Time dimensions of the gait cycle.	5
Figure 1.3	An example of variable step length.	6
Figure 1.4	Walking difficulties among non-institutionalised residents of the United States of America aged 65 years or older.	7
Figure 1.5	Falls rates in men and women (60-86 years) from the TASCOG study	12
Figure 1.6	Projected costs of falls related injuries in Australia 2001-2051.	13
Figure 1.7	Map of Australia	16
Figure 2.1	Gait parameter definitions	26
Figure 2.2	Visual contrast sensitivity	28
Figure 2.3	Proprioception	29
Figure 2.4	Maximal isometric knee extension	29
Figure 2.5	Simple reaction time	30
Figure 2.6	Body sway	31
Figure 4.1	Scatter plots and fitted regression lines of the relationship between age and each gait measure	58
Figure 5.1	Scatter plots and fitted regression lines of the relationship between age and each gait measure	86

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Appendix 4A

Callisaya ML, Au BT, Blizzard L, Schmidt MD, McGinley JL, Velandai KS, Subject-matter considerations in assessing the fit of a linear regression model. *Australasian Epidemiologist* 2007; 14.2:35-37

Chapter 5

Callisaya ML, McGinley J, Blizzard L, Schmidt M & Srikanth V, Age and gait variability – a population-based study of older people. *Age and Ageing.* 2010, 39(2):191-197

Chapter 6

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Chapter 7

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Papers Submitted

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Other publications

Srikanth KS, Beare R, Blizzard L, Phan T, Stapleton J, Chen J, **Callisaya M**, Martin K, Reutens D, Cerebral white matter lesions, gait, and the risk of incident falls: a prospective population-based study. *Stroke* 2009; 40:1:175-180

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Conference presentations arising from this thesis

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2005 The Australian Neurology and Gerontology Physiotherapy Conference, Melbourne
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2007 Joint Scientific Meetings of the Australasian Epidemiological Association (AEA) and the International Epidemiological Association (IEA), Western Pacific Region, Hobart
Sex modifies the relationship between age and gait - a population-based study of older adults
Published in the Australasian Epidemiologist 2007: Issue 14.3

2008 17th Annual Meeting of European Society of Movement Analysis in Adults and Children (ESMAC), Antalya, Turkey
Ageing and gait variability – a population-based study of older adults
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2009 International Society of Posture and Gait Research 19th Conference, Bologna, Italy
Sensorimotor correlates of gait variability in older people - A population-based study

Poster presentations

2006 The Australian and New Zealand Society for Geriatric Medicine (ANZSGM) Annual Scientific Meeting, Christchurch

The effect of age and sex on gait in a population-based study of older people –The Tasmanian Cognition and Gait Study

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List of abbreviations

ABS	Australian Bureau of Statistics
CI	Confidence interval
CNS	Central nervous system
DSP	Double support phase
DST	Double support time
ICC	Intraclass correlation coefficient
MRI	Magnetic Resonance Imaging
OR	Odds ratio
POMA	Performance Oriented Mobility Assessment
PPA	Physiological Profile Assessment
ProFaNE	Prevention of Falls Network Europe
QS	Quadriceps strength
RR	Relative risk
ROC	Receiver operator curve
SD	Standard deviation
SE	Standard error
SEO	Sway eyes open
SEC	Sway eyes closed
TASCOG	Tasmanian Study of Cognition and Gait
VCS	Visual contrast sensitivity

Chapter 1: Introduction

Life expectancy is currently greater than at any other time in history. Unfortunately these additional years of life are not necessarily spent in good health. Problems such as decline in mobility and falls are extremely common among older people. In community-residing people, the prevalence of walking impairments has been reported to be as high as 35% in those over 70 years of age and, each year, falls are reported to occur in over one third of those over 65 years of age [1-3]. Furthermore the prevalence of walking impairments and the incidence of falls tend to increase with age [1, 2]. The impacts of these conditions and falls events are significant in terms of loss of quality of life for the individual and health care costs for the individual and society [4, 5].

1.1 An aged and ageing population

There are an estimated 264 million people over 60 years of age in the developed world [6]. In Australia, based on the ABS census of 2006, 2.7 million people or 13% of the population were already over 60 years of age at that time [7]. Based on the proportions reported above, approximately 945,000 Australians of these ages have walking impairments and more than 900,000 suffer one or more falls each year.

The burden associated with walking impairments and falls is likely to be more pronounced in the future with the rapid ageing of the human populations. Of major importance is the shift in the age distribution that is occurring simultaneously with population growth in developed countries. Globally the number of people over 60 years of age is expected to triple by 2050 [6]. In Australia, it is projected that 8.1 million people or 23% of the population will be over 60 years of age in 2056 (ABS 2008, series B projection) [7]. The age distributions of the Australian population in 2006, and the projected distributions in 2056, are depicted in Figure 1.1. Among persons aged 60 years or older, the greatest proportionate increases in population size are expected in the age groups representing older people. The number of people over 85 years is projected to increase more than fivefold, and number of centenarians is estimated to increase by 25 fold (over 60,000 people), by 2056 (ABS 2008, Series B projection) [7]. Considering the high prevalence of walking impairments and falls among people of these ages, the investigation of preventive measures will increasingly become a public health priority.

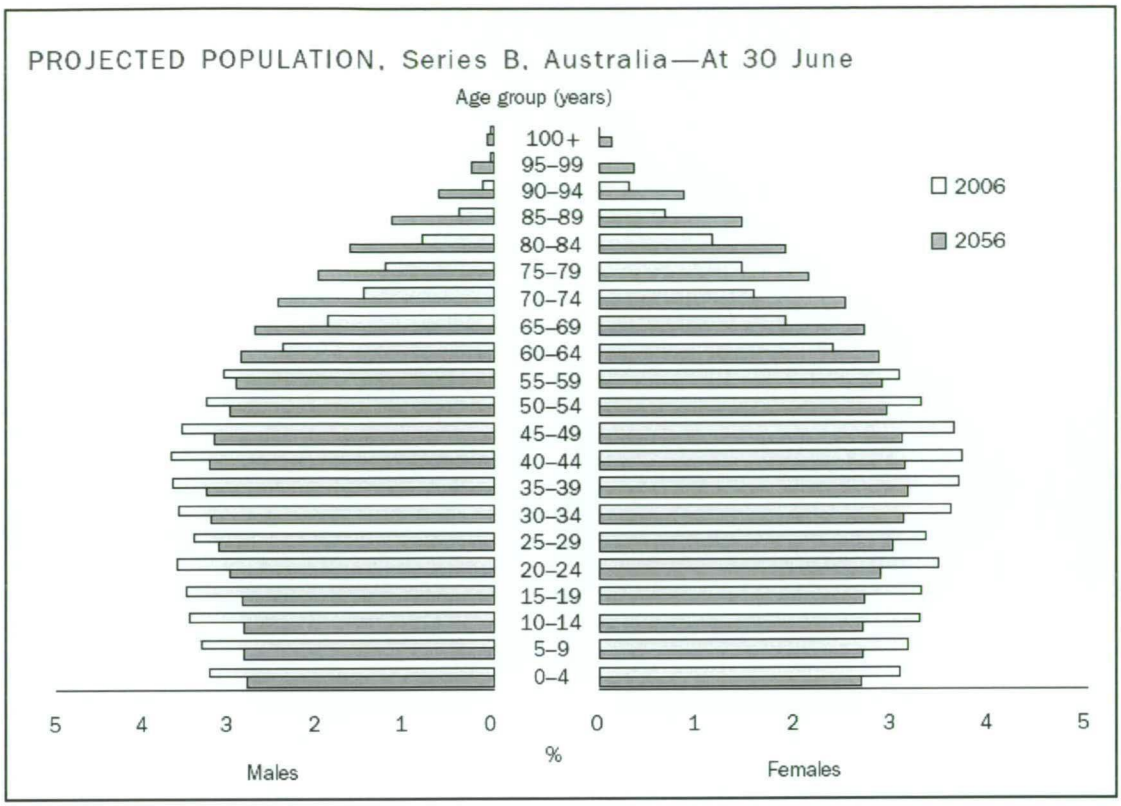


Figure 1.1 Population Projections Australia 2006-2056 (Source: ABS 2008, p 45)

The sections that follow provide a brief overview of the measurement, prevalence, costs and consequences of mobility impairments and falls, and of risk factors for them, in an aged and ageing population.

1.2 Mobility, walking and gait

Definition of mobility, walking and gait

The following definitions will be used in this thesis [8]:

> Mobility is the capability to move or be moved about readily from place to place. Mobility refers to a broad range of tasks such as transfers in and out of a bed, walking, climbing stairs and moving about outdoors. This thesis will focus on walking, which is the predominant form of mobility.
>
> Walking is the ability to advance or travel on foot by advancing the feet alternately so that there is always one foot on the ground.
>
> Gait is the way or pattern of walking.

How is walking measured?

Walking can be described qualitatively or measured quantitatively.

Qualitative descriptions of walking

Qualitative descriptions of walking are subjective assessments or interpretations of a gait pattern. Such descriptions include slow, shuffling, ataxic and asymmetrical. By themselves, these descriptions do not quantify level or change over time.

Quantitative measurements of walking

Quantitative gait analysis involves measurements of gait expressed as a quantity. These measurements quantify level, enable assessment of change over time, and can be used to provide statistical summaries and tests of hypotheses. There are a variety of ways that walking can be quantitatively measured.

The self-report questionnaire is a relatively simple method of collecting information about walking capability. A common approach is to question whether a person can walk a specific distance such as 400 metres. These questionnaires are useful in population surveys because they are quick and cheap to administer to a large number of people. This method relies on a person's estimate of their own ability, may not be sensitive to small changes in walking ability over time, and does not provide information about a person's gait pattern.

Several mobility scales have been developed to measure a person's gait pattern in clinical practice. Such instruments include the Modified Gait Abnormality Rating Scale [9] and the gait component of the Performance Orientated Mobility Assessment (POMA) [10]. These instruments rank various aspects of a person's walking pattern on a 2, 3 or 4 point scale. For example, the POMA evaluates gait characteristics such as step height, step length, continuity and symmetry, and path deviation on a 2 or 3 point scale. The advantages of these instruments are that they are cheap, require little (video camera) or no equipment, and are reasonably quick to use; however, these scales have a number of limitations. They rely on subjective decisions by the assessor about a person's walking pattern, and typically the measurements are not sufficiently responsive to small changes [9] or predictive of adverse events such as falling [10].

Measurements obtained in gait laboratories provide detailed information about a person's gait pattern. Measures include electromyography, kinematic and kinetics, and temporal-spatial parameters. Electromyography measures the firing of muscles during walking. Kinematics describes movement and angles of body segments and joints. Kinetics relates to the measurements of forces and moments that cause motion. Temporal-spatial parameters are measures of time and distance. These measures are on a continuous scale

of measurement with a true zero. This type of data is more discriminatory and allows a wider range of mathematical and statistical operations than those measured on an ordinal scale [11]. The disadvantages of these measurements recorded in a gait laboratory are that most require the use of time intensive, expensive and sophisticated equipment such as motion capture systems or force plates. Some measurements, such as electromyography, require equipment to be attached to the participant and this may alter the natural gait pattern.

Temporal-spatial variables can also be measured outside of a gait laboratory. Simpler methods include the use of a stop watch and tape measure, or a paper walkway and shoes with ink pads. With advancements in technology and computers, other tools such as footswitch systems and computerised walkways have become readily available to more accurately and efficiently collect data. Such instruments are not prohibitive in terms of expense for most hospitals and rehabilitation settings.

After reflection on the available measurements and instruments, temporal-spatial variables collected by a computerised walkway were selected for the studies of this thesis. Temporal-spatial measures were chosen as they provide quantitative information about a person's gait pattern that is more discriminatory than measurements using ordinal scales, but they do not require the use of expensive or time consuming equipment. The computerised walkway was chosen as it has the advantage of being able to measure both temporal and spatial gait variables; it is portable, can be used to efficiently take measurements on large numbers of people, and as mentioned above is not prohibitive in terms of expense. The disadvantages of computerised walkways are that testing cannot easily be undertaken outside in real life situations, and that the number of steps obtained in one walk depends upon the length of the walkway. To obtain a larger number of steps, walks need to be combined. This precludes analysis of variation in performance at different stages of longer walks (referred to as analysis of long range correlations).

Temporal-Spatial gait variables

Gait speed is the most commonly measured temporal-spatial gait variable and is equal to distance walked divided by time taken. The determinants of gait speed are step length and cadence. Cadence is the number of steps taken per minute. Step length and other temporal-spatial variables such as step time, step width, swing phase, stance phase and double support phase relate to the gait cycle and are described below.

The Gait Cycle

One gait cycle extends from the initial contact of one foot with the ground to the stage when the same foot contacts the ground again (right heel contact to right heel contact in Figure 1.2). One gait cycle contains two steps. One step is from the initial contact of one foot with the ground to the initial contact of the opposite foot with the ground (right heel contact to left heel contact in Figure 1.2). A step can be measured in terms of distance (step length) or time (step time) in the sagittal plane, or by the distance between the feet in the frontal plane (step width). The gait cycle can be broken up into phases that can be measured in terms of time or percentage of the gait cycle (Figure 1.2). Stance phase is the period of the gait cycle when one foot is in contact with the ground, whereas swing phase is the period of the gait cycle when the foot is not in contact with the ground. During the gait cycle approximately 60% is spent in stance phase and 40% in swing phase. Stance phase can be further divided into two double support phases (when both feet are in contact with the ground) and one single support phase (when only one foot is in contact with the ground).

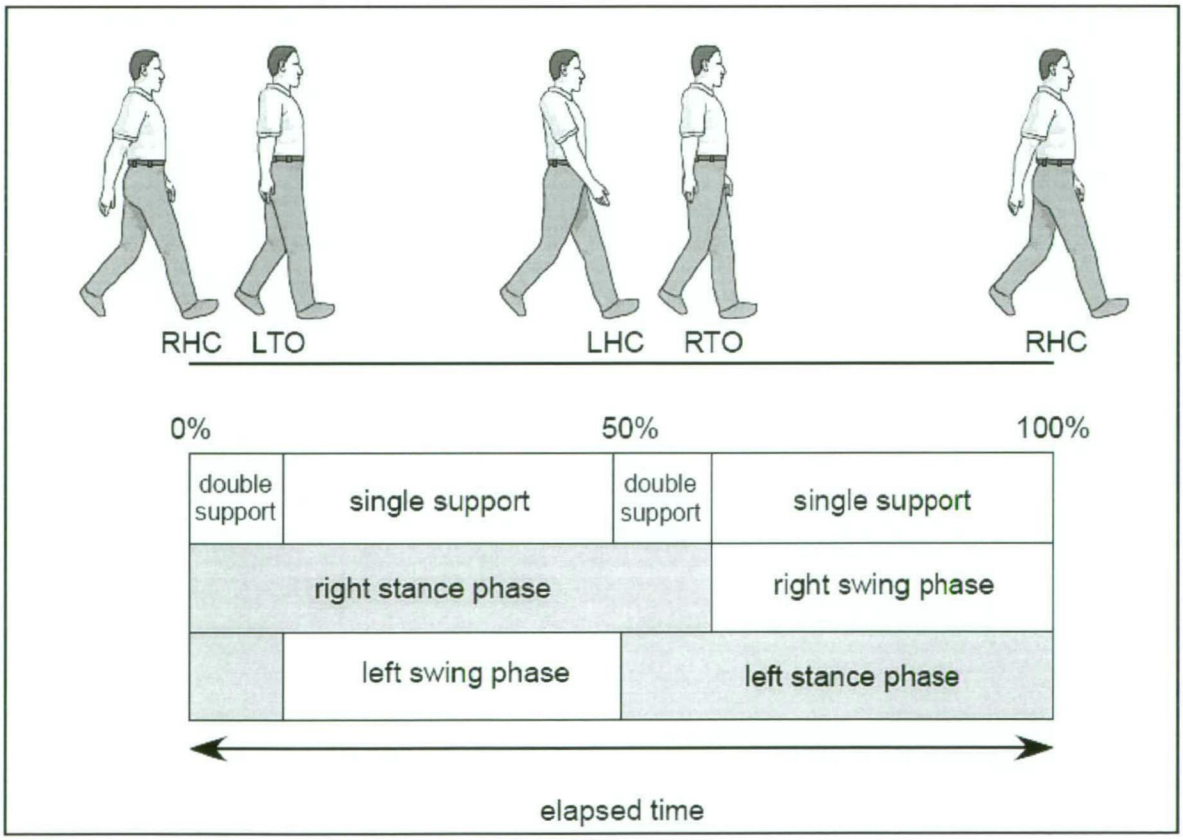


Figure 1.2 Time dimensions of the gait cycle. RHC=right heel contact; LTO=left toe off; LHC=left heel contact; RTO=right toe off (Used with permission from Associate Professor Hylton Menz, La Trobe University, Melbourne, Australia).

Multiple gait cycles are usually measured across a walk, and the above mentioned temporal-spatial variables are recorded as the average of each gait variable across all gait cycles measured (For example the average of step length in Figure 1.3 would be 45.62cm). These average measures of gait do not measure the variation that occurs between successive steps (For example, the average of step length does not provide information regarding whether all steps are of similar length or highly variable as in Figure 1.3). The fluctuation or variance in a gait measure from one step to the next (gait variability) may be a more sensitive indicator of walking instability and falls risk [12]. Gait variability measures that have been described include variability of gait speed, step length, step width, step time, swing time, stance time and double support time [13-15].

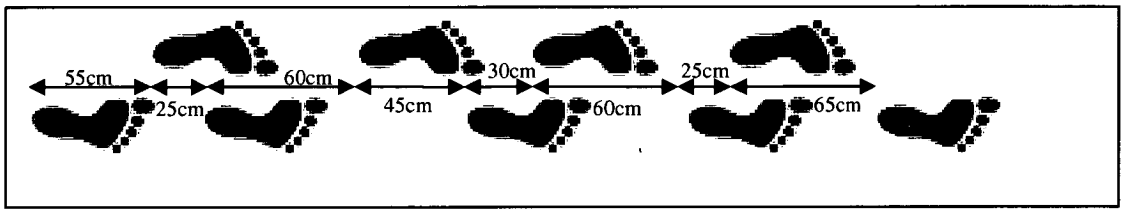


Figure 1.3 An example of variable step length

Prevalence of walking disability in the general population

Walking disability is common in older age. The majority of population-based data on walking disability are sourced from the United States of America (USA). The 2006 USA Medicare Current Beneficiary Survey, using self-reported data, determined that 23.7% of community dwelling people older than 65 years of age had at least some difficulty walking alone without equipment [16]. Only a small percentage (3.1%) of people older than 65 years of age among subjects in the 2007 National Health Institute Survey [16] needed assistance to get around inside the home. However, a larger percentage (40.4%) reported at least some difficulty walking 440 yards and nearly 16 percent (12.4% men, 18.7% women) reported being unable to walk that distance. The percentage of people with walking limitations increased with age (Figure 1.4) and women had greater difficulty than men [16]. An Australian population-based study determined 23% of community-dwelling people older than 65 years of age (n=995) had self-reported difficulty walking one kilometre [18]. The limitations of self-reported data have been discussed earlier in this chapter. More sensitive measures are required to detect small changes over time.

Costs and consequences

The ability to undertake physical activity is important to maintain an independent and healthy lifestyle. In Australia walking is the most common physical activity undertaken by those aged 65 years or older [19]. Adequate walking ability is also needed to participate in social and other physical activities enjoyed by older people such as golf and lawn bowls [20]. The benefits of walking include improved cardio-respiratory health, mental wellbeing, reduction of risk for some cancers and maintaining sufficient bone and muscle strength [21]. In contrast walking impairment can make day to day activities such as self care, housework and shopping extremely difficult [22]. Inability to carry out activities of daily living may lead to social isolation, the need for a carer, or admission to residential care [23].

It is not just the ability to walk that is important. Maintaining an adequate level of performance is also necessary. Gait speeds of less than 1 m/sec have been reported to be predictive of future falls, nursing home admission and even death [5, 24]. Minimum levels of gait speed are also needed to function in the community. For example, based on current traffic light settings, a speed of 1.2 m/sec is needed to cross the road at an intersection in Australia [25].

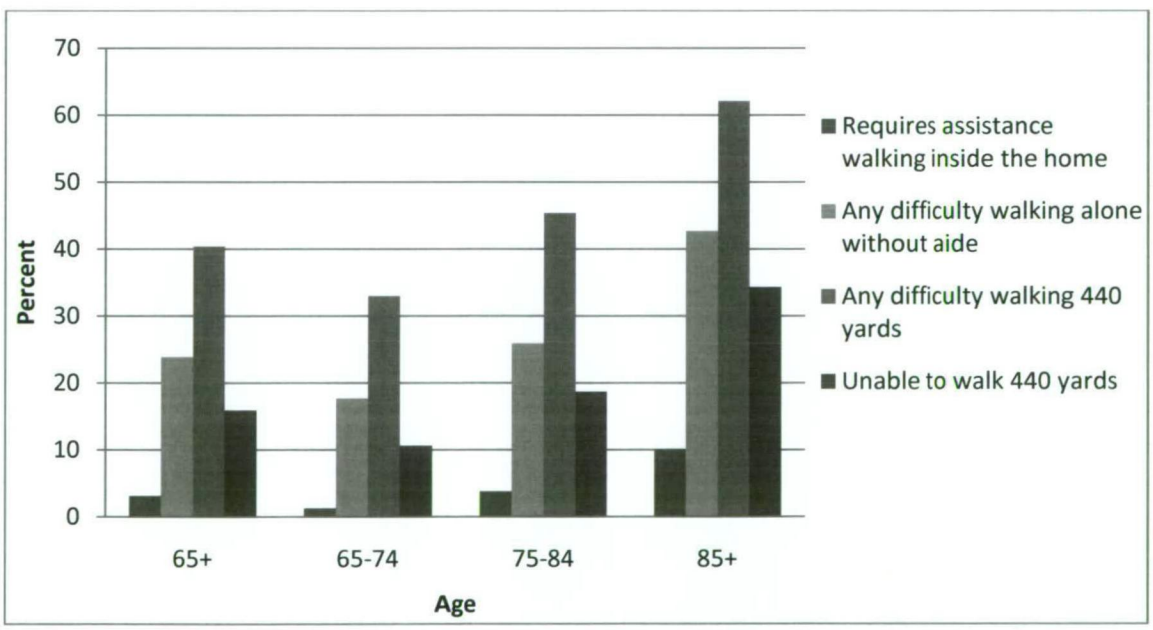


Figure 1.4 Walking difficulties among non-institutionalised residents of the United States of America aged 65 years or older (Adapted from the Medicare Current Beneficiary Survey 2006 and the National Health Institute Survey 2007)

The social and economic costs associated with walking impairments and related adverse events such as falls are already high due to the current large numbers of older people in Australia and other Western populations. With the ageing of populations, the costs are likely to increase significantly in future years. A greater understanding of how walking is affected by advancing age is required to assist in better targeting of persons for interventions to prevent loss of independence. This subject is examined further in chapters 4 and 5, which report on the relationship between age and a wide range of temporal-spatial gait measures.

Factors influencing impairments in walking in older people

A number of risk factors for impaired walking have been identified in people over 60 years of age. Specific chronic conditions that are more prevalent among older persons - such as heart attack, stroke, dementia, Parkinson's disease, diabetes, high blood pressure and cancer - have been associated with poorer gait patterns [22]. Age, sub-clinical disease or disease-related changes in physiological and cognitive function, pain, psychological conditions and social factors have also been associated with poorer walking performance [22, 26].

The physiological factors associated with gait include sensory, motor and integrative systems (collectively termed sensorimotor functions). This thesis will concentrate on those considered important for the production of walking.

Decline in sensorimotor functions as risk factors for impaired walking in older people

Changes in walking patterns of older people may arise in relation to endogenous or exogenous factors [27, 28]. The systems in the human body may be genetically programmed to decline with age at a certain rate, suggesting that decline in walking in older age is inevitable. Alternatively, older people may continue to function as well as younger people unless the person is exposed to an external cause of impairment, such as an acquired disease, smoking, inactivity or poor nutrition that may affect one or a number of body systems. This suggests that functions such as walking remain unimpaired if a person maintains a healthy lifestyle (for example by exercising, eating well and not smoking) [28].

It is likely that decline in walking ability occurs due to a combination of 'endogenous' and 'exogenous' ageing. Irrespective of which pathway results in walking impairment, decline in sensorimotor systems is likely to play a part.

The body's sensorimotor systems are important when walking for the maintenance of postural stability, co-ordination of joints and muscles and forward propulsion [29]. Sensory input from the visual, vestibular and somatosensory systems is processed in the central nervous system (CNS) to produce a timely and co-ordinated motor output. The effect of advancing age and of subclinical or clinical disease on such sensorimotor factors is likely to subsequently impact on walking performance [29]. A brief description of the contribution of age- or disease-related decline in each sensorimotor factor to walking performance is given below:

Lower limb muscle strength

Lower limb muscle strength is the force that a muscle can produce with a single maximal effort. A number of studies have reported that lower limb muscle strength declines with advancing age [30-32]. A decline in muscle strength is likely to result in reduced postural stability and less forward propulsion when walking [33].

Lower limb peripheral sensation

Peripheral sensations include proprioception, vibration sense and discriminative and light touch. Decline in lower limb peripheral sensation has been associated with older age [30]. Decline in lower limb peripheral sensation may result in reduced postural stability, difficulty walking over rough surfaces, inaccurate timing and placement of feet and contact with obstacles.

Vestibular function

The vestibular system stabilises eye movements and posture by detecting linear and angular accelerations and integrating this with information from other sensory systems to maintain upright stance. Older people have poorer vestibular function [30]. Decline in the vestibular system may lead to a more unstable, uncoordinated or more variable gait pattern due to inaccurate information being processed in the CNS.

Vision

Vision provides a person with information about the environment and the position and movement of the body in relation to the environment [34]. Vision includes measures of visual acuity, visual fields, edge contrast sensitivity and depth perception [30]. Poorer performance in such tests are associated with older age [30]. Visual impairment may lead to poorer postural stability, trips over unseen

obstacles, difficultly adapting to undulating terrain and problems with navigation [34].

Reaction time

Reaction time is the delay from a stimulus signalling a needed reaction to making a movement or developing a force, and is likely to represent a combination of central and peripheral processing speeds. Reaction time is important because it has a bearing on the speed with which postural corrections can be made in response to internal or external perturbations. Reaction time is slower in older age [30]. Slower reaction time may lead to a more variable gait pattern due to the inability to process incoming and outgoing information in a timely manner, and to events such as falls due to slower postural corrections.

Balance

In standing, the ability to balance (measured by the amount of postural sway) declines with advancing age [30, 31]. Although balance in standing is different to balance whilst walking (where the centre of mass is outside of the base of support for much of the gait cycle) [35], balance ability in both tasks may be representative of how well the body is processing and integrating incoming sensory and outgoing motor information. Poorer balance may lead to a more unstable and variable gait pattern. Alternatively poorer balance may result in compensatory strategies such as a longer double support phase or a wider step width as an attempt to regain stability.

The mechanisms underlying walking decline in older people are likely to be complex and varied. Although age- or disease-related decline in a single sensorimotor factor may affect walking performance, it is more likely to be due to the complex interactions of a number of sensorimotor factors each in age- or disease-related decline [36-38]. Few studies have examined the effect or complex interactions of decline in multiple sensorimotor systems on gait patterns in older people [26, 29, 39, 40]. A better understanding of which sensorimotor factors are associated with different temporal-spatial gait variables may lead to more specific interventions to reduce or prevent mobility decline in older people. This topic will be investigated in chapters 6 and 7.

1.3 Falls in older people

Definition of falls

A systematic review of interventions to prevent falls reported that there was no single definition of falls [41]. To address this issue, the Prevention of Falls Network Europe (ProFaNE) organised a team of international experts to meet with the purpose of developing a standard definition for falls after an extensive literature review. A consensus statement included the recommendation that a fall be defined as 'an unexpected event in which the participant comes to rest on the ground, floor, or lower level' [42].

How are falls measured?

Information on falls in the community can be collected in two main ways. The first is by retrospective reporting or recall of falls. This involves asking participants whether and how often they have fallen in a recent period (for example, the previous 6-12 months). This method may result in underestimation or overestimation of the actual number of falls due to recall bias, that is, the participant may inaccurately recall the number of falls that occurred. The second method (the method chosen for the study of gait and falls in this thesis) is by prospective reporting. Participants are followed up over a period of time (for example 12 months). Information on falls is obtained at the end of that time or, more usually, by having participants report at regular intervals (say weekly, monthly or every two months) on falls that occurred during the intervening period. To enable reporting, participants generally complete a questionnaire or postcard and return it to the research team. Collection can be improved by having participants complete a falls diary or calendar on a daily basis, and by using telephone calls to remind participants that fail to return questionnaires [41, 42]. There is some evidence that prospective reporting in this way may help reduce measurement error. In a study of healthy older women, prospective collection of falls over 12 months (using a falls diary and monthly phone calls) improved recall of falls by 14.8% when compared with retrospective recall of falls at the end of the collection period [43].

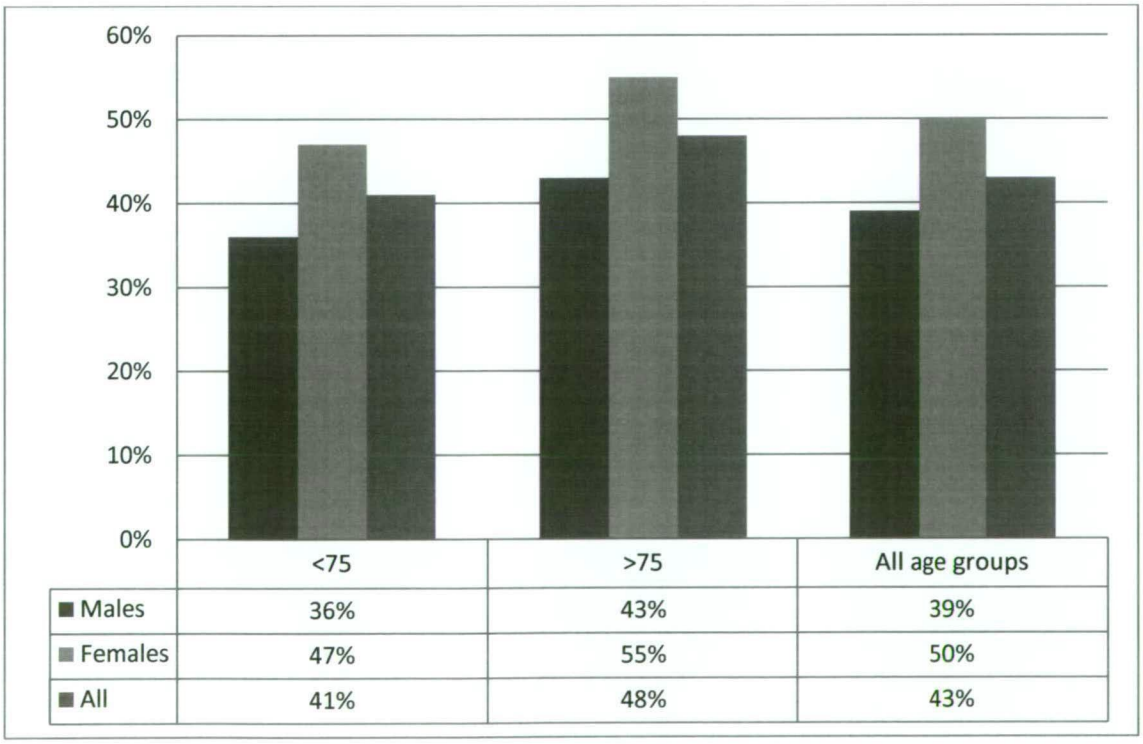
Incidence of falls in older people

Falls in older people are extremely common. In prospective population-based studies of community dwelling people over 65 years of age, 32-49% have been reported [3, 44-48] to fall at least once in a one year period. The proportion of people falling more than once in a one year period ranges from 11-22% [44-46, 48].

The proportion of older people falling also appears to increase with age [2]. Unpublished data from the TASCOG project are shown in Figure 1.5. The proportion of falls was greater for those age 75 years or over (48%) than for those aged less than 75 years (41%). As has been reported in other studies [3], the women in this sample had higher rates of falls than men.

Costs and consequences of falls

The costs and consequences of falls for the individual, families and society are significant. Around 40-60% of falls lead to an injury [49] . Most result in soft tissue injuries such as bruising and abrasions [49], but approximately 24% lead to serious injury [47] and 5% result in a fracture [47, 49]. Although only about 1% of falls result in a hip fracture [50], those that do are usually the most expensive. Furthermore, after 12 months following a hip fracture, less than 50% of those affected have recovered to pre-fracture level of functioning in personal and instrumental activities of daily living [51]. Falls are the leading cause of injury-related hospitalisation in older people [52] and increase the risk of nursing home admission [53] and mortality [4]. In Australia, according to Australian Health and Welfare Institute data 2005-2006, the age standardised rate of fall injury hospitalisation cases was 2,415 per 100,000 population for people aged 65 years or over [54]. Falls, whether they result in injury or not, may also lead to fear of further falls, loss of confidence and activity restriction [55].



	<75	>75	All age groups
Males	36%	43%	39%
Females	47%	55%	50%
All	41%	48%	43%

Figure 1.5 Falls in men and women (60-86 years) from the TASCOG study (n=361)

The monetary costs of falls are very high. In the United States, an estimated 19.2 billion dollars was spent on falls-related costs in 2000. Of this, 0.2 billion dollars was for fatal falls and 19 billion for non-fatal falls [4]. Of the costs associated with non-fatal falls, 63% was spent on hospitalisations, 21% was spent on emergency department visits, and 16% was spent on treatment in outpatient settings. In Australia the total health costs associated with falls is projected to triple to nearly 1.4 billion dollars by 2051 (Figure 1.6) [56]. Furthermore it is projected that 886,000 extra hospital bed days will be used per year in 2051 to treat persons injured in falls, and an additional 3320 nursing home places will be required to cater for those who cannot return home [56].

Risk factors for falls in older people

Falls are thought to be due to a combination of intrinsic (e.g. reduced muscle strength, poor balance, visual deficits and cognitive impairment), extrinsic (e.g. polypharmacy and psychotropic medications) and environmental (e.g. rugs and poor lighting) factors [57, 58]. For example, an older person may trip on a mat (environmental factor) due to poor vision (intrinsic factor), or fall because they are unable to maintain balance due to slow reaction times caused by benzodiazepine medication (extrinsic factor).

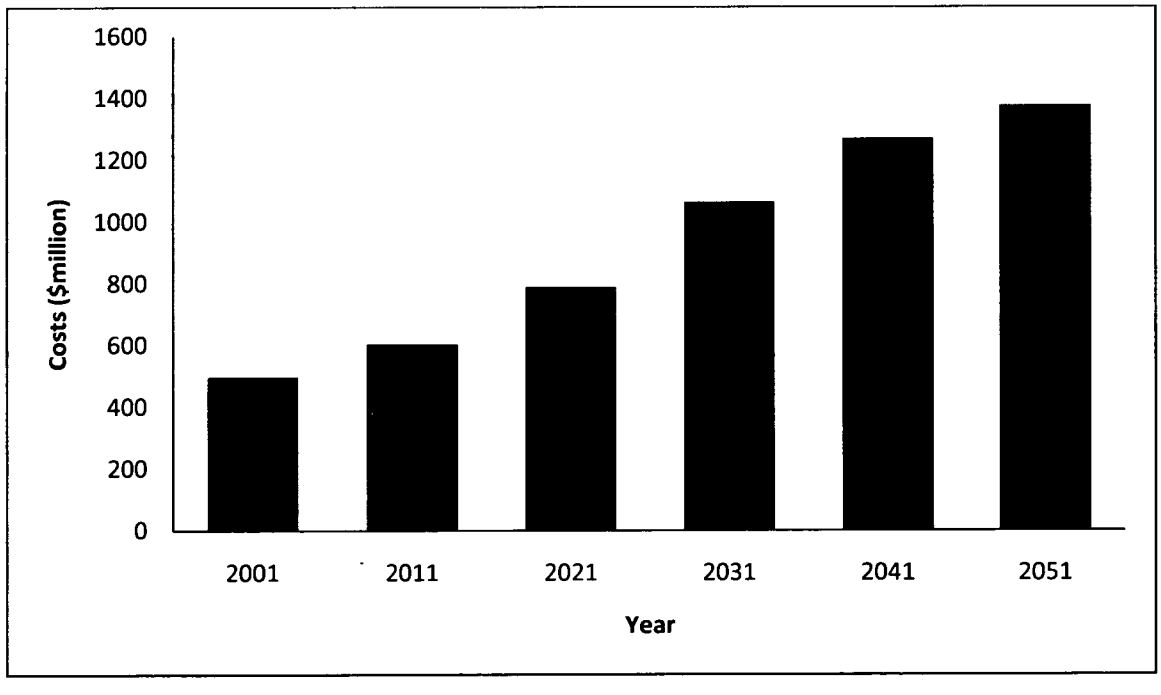


Figure 1.6 Projected costs of falls related injuries in Australia 2001-2051. Adapted from Projected costs of fall related injury to older persons due to demographic change in Australia, J. Moller, 2003 [56].

The risk of falling appears to increase as the number of risk factors increase [47, 59]. In a study of community-dwelling older people, the percentage of people falling multiple times

increased from 10% in those with none or one risk factor to 69% in those with four to seven risk factors [59].

Walking as a risk factor for falls in older people

A recent meta-analysis indentified gait and balance problems as the most consistent predictors of future falls [60]. There are a number of characteristics of walking that may explain why such a large number of falls occur during this activity.

Firstly, walking is an extremely unstable activity that has been described as a series of controlled falls because the body is continuously losing and regaining balance [61]. Two-thirds of the body's weight is located two thirds of the distance up off the ground and supported on only one foot for most of the gait cycle. Even in the small amount of time that two feet are on the ground, they are not fully flat with one foot partly in heel strike and the other partly in push off position. Furthermore, the centre of gravity lies outside the base of support for much of the gait cycle and this further challenges postural stability [62].

Secondly, regulation of upright stance whilst walking relies on the precise and complex interaction between the peripheral and central nervous systems. Disruption to one or more systems is likely to negatively affect postural stability and walking performance. Therefore walking performance may represent a good summary measure of the body's ability to compensate for the accumulation of impairments in these systems, and also be a sensitive measure of falls risk.

Chapter 8 reports an investigation of whether poorer performance on a range of temporal and spatial gait measures increases the risk of falling.

1.4 Summary

Walking impairments and associated adverse events such as falls are extremely common in people over 60 years of age. The consequences of such problems are often severe, and include injury, hospitalisation and need for residential care. In developed countries, the costs associated with these major public health problems are significant due to the current high numbers of people over 60 years of age. The magnitude of these problems has already begun to increase as the numbers and proportions of older people around the world rise rapidly. There is urgent need to identify those at risk and determine the factors that may be used as therapeutic targets in preventive programs.

Age- or disease-related decline in the body's sensorimotor systems may adversely impact on the walking performance of older people. Identification of the sensorimotor factors that contribute to poorer gait patterns may provide therapeutic targets for programs aimed at maintaining walking independence. Further, if the ability to walk relies on the precise co-ordination of a number of these sensorimotor factors, measures of gait may provide a summary measure of how well a person is functioning and be sensitive predictors of future falls risk.

1.5 Overview of the investigation reported in this thesis

Aims

The aims of this thesis are to investigate in a population-based sample of community-dwelling older people:

1. the relationships between age, sex and a range of temporal-spatial (i) gait and (ii) gait variability measures;
2. the relationships between sensorimotor factors and temporal-spatial (i) gait and (ii) gait variability measures;
3. whether poorer performance in a range of temporal-spatial gait and gait variability increases the risk of falling.

Study population

The study population for this thesis is drawn from southern Tasmania. Tasmania is the island state of Australia (Figure 1.7). In 2002, 14.0% of the Tasmanian population was already aged 60 years or older compared with a national percentage of 12.7%. It is estimated that Tasmania will have the oldest population among all states and territories of Australia by 2051, with the percentage of the population aged over 65 years expected to more than double to 34% (ABS 2003, Series B projection) [63]. In 2006, southern Tasmania had a total population of 239,444 people including 46,159 persons (19%) aged at least 60 years [64]. This high proportion of older people in southern Tasmania makes it an ideal population for this study.

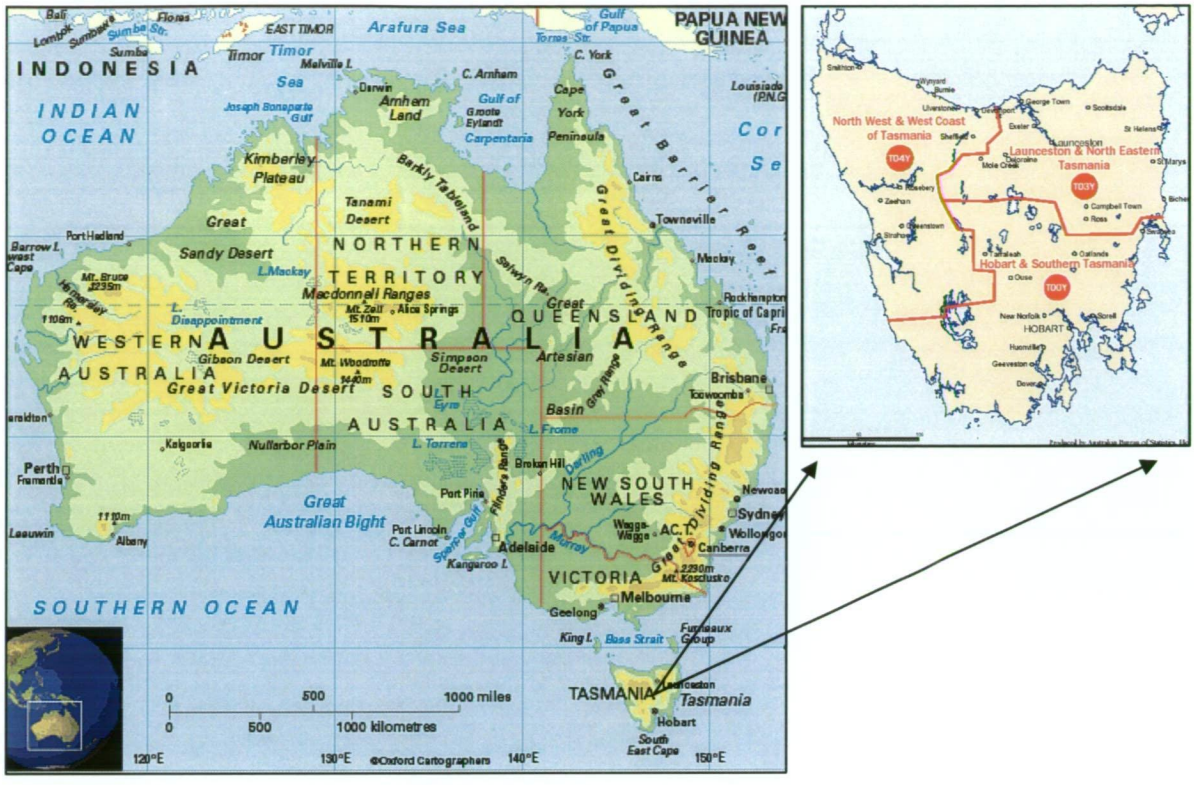


Figure 1.7 Map of Australia (Source: With permission from the Commonwealth Secretariat, http://www.thecommonwealth.org/)

1.6 Structure of this thesis

Chapter 2: Materials and methods. This chapter briefly describes the study sample and presents an overview of the materials and methods used to measure gait, sensorimotor function and falls.

Chapter 3: Issues in the measurement of the gait parameters. This chapter presents results of a study to determine how many walks on a computerised walkway are required to represent the mean of six walks in a population-based sample of 367 community-dwelling older people aged 60-86 years. It also presents results from an examination of test-retest reliability of the gait variability measures in a sample of 16 volunteers aged 60-86 years.

Chapter 4: Sex modifies the relationship between age and gait - a population-based study of older adults. This chapter reports the cross-sectional associations between age and a number of temporal and spatial gait measures in a population-based sample of 223 community-dwelling people aged 60-86 years. The text of this chapter has been published [65]. That of Appendix 4A (Subject-matter considerations in assessing the fit of a linear

regression model) reports the results of a statistical investigation of the outliers in the walking speed data. It too has been published [66].

Chapter 5: Age and gait variability – a population-based study of older people. This chapter presents the findings from a cross-sectional study examining the associations between age and a number of gait variability measures in a randomly selected sample of 412 community-dwelling people aged 60-86 years. The text of this chapter has been accepted for publication [67].

Chapter 6: A population-based study of sensorimotor factors affecting gait in older people. This chapter reports an analysis of the associations of a range of sensorimotor measures with temporal and spatial gait measures in a random sample of 278 community-dwelling men and women aged 60-86 years. The text of this chapter has been published [68].

Chapter 7: Sensorimotor factors affecting gait variability in older people - a population-based study. This chapter investigates the associations of a range of sensorimotor measures with temporal and spatial gait variability measures in a sample of 412 community-dwelling people aged 60-86 years. This study has been published [69].

Chapter 8: Gait, gait variability and the risk of multiple incident falls in older people - A population-based study. This chapter examines whether poorer performance on measures of gait increases the risk of falls in a population-based sample of 412 community-dwelling men and women aged 60-86 years. The text of this chapter has been submitted for publication [70].

Chapter 9: Summary. This chapter summarises the findings, presents the conclusions of the thesis and suggests directions for future research.

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Chapter 2: Methods

2.1 Preface

The aims of this thesis are to describe gait patterns and their underlying sensorimotor factors, and to investigate whether these gait patterns increase the risk of falls in community dwelling older people. This chapter provides a description of the study factors investigated in the studies reported in this thesis, and the methods employed to measure them. It commences by briefly outlining the over-arching project of which this work forms part, and the study population for the project.

2.2 The Tasmanian Study of Cognition and Gait

This work is a sub-study of a larger project, the Tasmanian Study of Cognition and Gait (TASCOG). The broad aims of TASCOG are to examine the effects of brain ageing on gait, balance and cognition. A further aim of the study is to discover factors that can be modified or treated in order to prevent dementia and falls in older people. The work that forms this thesis specifically examines age-related gait patterns with the aim of identifying underlying sensorimotor factors that can be modified or treated in order to prevent walking impairments and falls in older people.

2.3 Study population

The study population included people aged 60-86 years residing in southern Tasmania (postcodes 7000-7199). Tasmania is the southern (41-43°S) island state of Australia with a population of 485,300 persons in 2005 [1]. Southern Tasmania includes the capital city of Hobart and surrounding areas with a total population of 239,444 people including 46,159 persons aged at least 60 years [1]. Participants were included if they could walk without the use of a gait aid and were able to understand simple commands in English. Participants were excluded if they lived in a nursing home or if they had any contraindications to magnetic resonance imaging (MRI) that was a procedural requirement for the TASCOG participants.

2.4 Study samples

Test re-test reliability study (Chapter 3)

Participants were 16 volunteers (aged 60-86 years) recruited from friends and family of staff at the Menzies Research Institute, University of Tasmania, Tasmania, Australia.

Other studies in this thesis (Chapters 3-8)

Participants (aged 60-86 years) were residents of southern Tasmania who were selected from the Tasmanian electoral roll using stratified random sampling with stratification by age (5 year age groups) and sex. An invitation to participate was sent by mail, followed by a telephone call. Multiple contact attempts were made if a person was initially un-contactable. Testing was conducted at the Menzies Research Institute, Hobart, Tasmania, Australia from December 2004 to December 2008.

The studies described in chapters 3 (study of the number of walks needed) and chapters 4-8 included the following participants from the TASCOG:

Chapter 3:	The first 367 participants to complete six walks on the computerised walkway.
Chapter 4:	The first 223 participants enrolled.
Chapter 6:	The first 278 participants enrolled.
Chapters 5,7 and 8:	412 participants (the full sample).

Analysis for the studies described in chapters 4 and 6 were undertaken before data for the full sample were collected.

2.5 Study factors

Average measures of Gait

Gait variables (gait speed, cadence, step time, step length, step width and double support phase (DSP)) were measured using the 4.6 metre *GAITRite* system (CIR Systems Inc. Clifton NJ, USA). The *GAITRite* is a portable carpet walkway with embedded pressure sensors that collects gait data electronically as the participant walks on the carpet. The active area is 61cm wide and 366cm long and contains 48 x 288 sensors. Data were sampled at 80Hz allowing a temporal resolution of 11 milliseconds. Participants without shoes started walking, two metres before the mat, and continued two metres past the mat,

to allow for acceleration and deceleration. The instruction given was: "Start walking at your normal walking speed". After two practice trials, participants performed six walks at their preferred speed. Participants stood between each walk for the time it took for the computer to process the data (usually less than 30 seconds) before commencing the next walk. Using the *GaitRite* software, the six walks were combined into one test. This was done for two reasons. Firstly, the *GaitRite* software automatically calculates the average of all walks in the test for each gait measure. Secondly, individual step measurements from the six walks can be exported as a group for each participant, rather than as six individual walks.

For the purpose of this research, the gait variables were defined as follows:

Gait speed (cm/sec)	Distance divided by the ambulation time
Cadence (steps/min)	The number of steps taken in one minute
Step time (sec)	The time from first contact of one footfall to the first contact of the opposite footfall
Step length (cm)	The perpendicular distance between from the heel point of one footfall and the next (In Figure 2.1 right step length is line AL and left step length is line LG).
Step width (cm)	The perpendicular distance from heel point of one footfall to the line of progression of the opposite foot (line DL in Figure 2.1)
DSP (% or sec)	The percentage or time in the gait cycle that both feet are in contact with the ground.

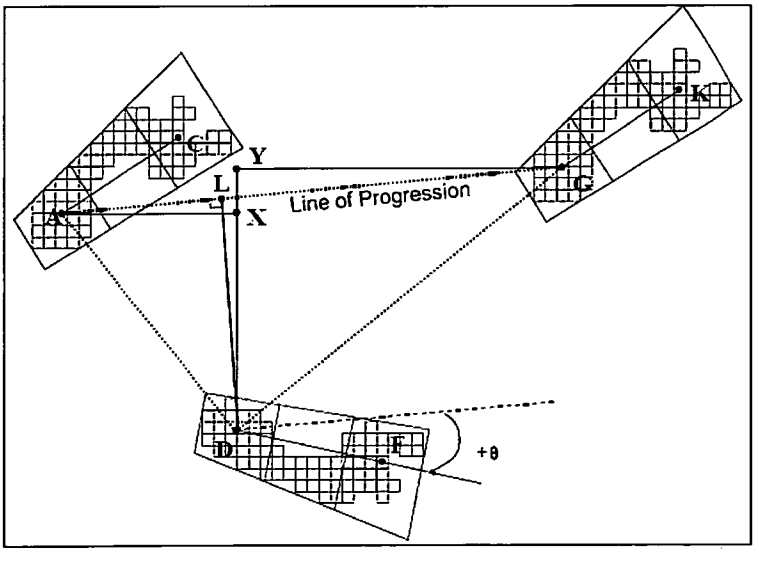

Figure 2.1 Gait parameter definitions
(Figure used with permission from CIR Systems Inc [2])

Validity and reliability of the gait measures recorded on the GaitRite walkway

For people aged 54-83 years (n=10) who were 12 months post unicomparmental knee replacement, the *GaitRite* system has demonstrated high concurrent validity (ICCs ranging from 0.92 to 0.99) relative to a three-dimensional motion analysis system for gait speed, cadence, step length and step time averaged across one walk [3]. In the same study the *GaitRite* system also demonstrated high concurrent validity for step length (ICC=0.99) and step time (ICC=0.91) measured as individual footsteps [3].

The test-retest reliability of temporal-spatial gait measures recorded on a *GaitRite* walkway has been assessed [4, 5] and the results are summarised in Table 2.1.

Table 2.1 Reliability of gait measures from 2 different studies

Measure	$ICC(3,1)$	(95% CI)*	$ICC(2,k)$	(95% CI)†
Gait speed	0.91	(0.83, 0.96)	0.96	(0.91,0.99)
Cadence	0.82	(0.66, 0.91)	-	-
Step time, right leg	-	-	0.95	(0.91,0.97)‡
Step time, left leg	-	-	-	-
Step length, right leg	0.89	(0.78, 0.94)	0.97	(0.95,0.98)‡
Step length , left leg	0.88	(0.77,0.94)	-	-
Step width, right leg	0.56	(0.26, 0.76)	0.80	(0.50,0.92)‡
Step width, left leg	0.49	(0.16,0.71)	-	-
Double support phase	-	-	0.93	(0.87,0.96)‡

Notes: ICC=intraclass correlation coefficient; CI=confidence intervals; - = not assessed

*Test and retest conducted approximately two weeks apart for people aged 76-87 years (n=31) with on each occasion the average of measurements from three trials used as the data for each subject in analysis [4]. $ICC(3,1)$ is appropriate when the occasion (test or retest) is considered to be a fixed source of variation, and the intention is to use the measurements from a single occasion as the data for each subject in the main study.

†Test and retest conducted one week apart for people aged 19-59 years (n=21) with on each occasion the average of the first ten steps from eight trials was used as the data for each subject in analysis [5]. $ICC(2,k)$ is appropriate when the occasion (test or retest) is considered to be a random source of variation, and the intention is to used the average of test and retest measurements as the data for each subject in the main study.

‡ Combined left and right side

In studies of association, the generally lower ICCs for step width suggest that the associations of study factors such as age and sensorimotor variables with step width are more likely to be obscured by random error than are the associations with other gait measures.

Gait variability measures

Variability in step time, step length, DSP and step width was assessed by combining individual step measurements from the six walks to calculate the standard deviation of each gait measure. There has been little work examining the test-retest reliability of gait variability measures [6]. This will be investigated in the following chapter (Chapter 3).

Sensorimotor function

Sensorimotor function was assessed using the protocols of the short form of the Physiological Profile Assessment (PPA), which includes measures of vision, proprioception, quadriceps strength, reaction time and postural sway (see following). The short form of the PPA comprises the five tests of sensorimotor function that were found to be the most important in discriminating between multiple fallers and non-multiple fallers in studies conducted by Lord et al [7-10]. In a prospective study of community-dwelling older women, the PPA measurements correctly classified multiple and non-multiple fallers with 75% accuracy [9]. Although other factors may be important in the control of gait, these five measures were included in this thesis because they are easily measured, quantitative, reliable, come as part of a validated falls risk screening assessment, and are modifiable or amenable to treatments delivered by health professionals [7]. The tests are as follows:

Visual contrast sensitivity

Visual contrast sensitivity (VCS) (dB) was measured using the Melbourne Edge Test (printed card) in a fluorescent lit room. The test consisted of a chart with 20 circles containing edges of reducing contrast and orientation (Figure 2.2). The participant was asked to identify the direction of the edge (horizontal, vertical, tilted right or tilted left). The lowest contrast identified was recorded in decibel units ($dB = -10\log_{10}$ contrast).

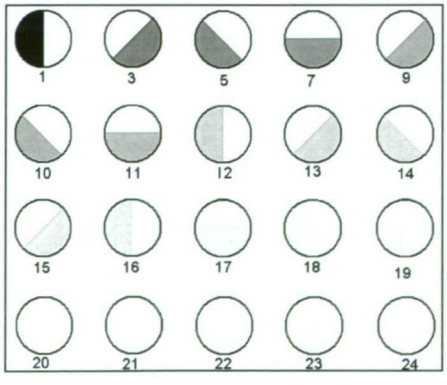

Figure 2.2 Visual contrast sensitivity

Proprioception

Proprioception (degrees) was assessed using a lower-limb matching task (Figure 2.3). Participants were asked to close their eyes and attempt to align their first (big) toes on each side of a clear acrylic sheet placed vertically between their feet. The sheet was marked with a protractor (60×60×1 cm) at two degree intervals. The difference between the left and right sides were measured in degrees. The final result was the average of five trials.

Figure 2.3 Proprioception

Maximal isometric quadriceps strength

Maximal isometric quadriceps strength (kg) was measured in sitting position using a spring gauge (Figure 2.4). The participant sat on a high chair with their hips and knees in 90 degrees flexion. A spring gauge was fixed to the back of the chair and attached to the patient at the ankle approximately 10cm above the lateral malleolus. The participant was asked to straighten their knee as far as they can with maximum force. The greatest force exerted on the spring and registered on the gauge in kg from three trials was recorded.

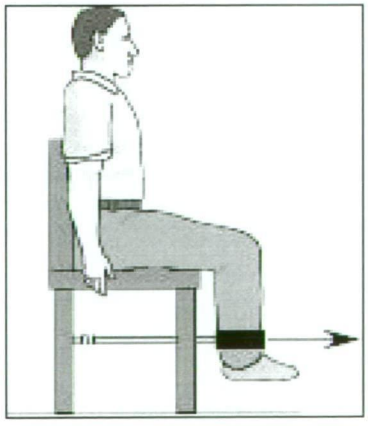

Figure 2.4 Maximal isometric quadriceps strength

Simple reaction time

Simple reaction time (milliseconds) was measured using a light stimulus and a finger-press of a switch as the response (Figure 2.5). The light stimulus and switch were located on a computer mouse that was connected to an electronic timer. The timer had a built-in variable delay of one to five seconds to activate the light stimulus. The participants placed their dominant hand on the computer mouse. They were then asked to press the switch on the mouse as soon as they saw the light turn on. They completed 10 practice trials before completing the 10 recorded trials. The difference between the time at which the light came on and the time at which the switch was pressed was recorded by the electronic timer and the average of the 10 trials was their final result.

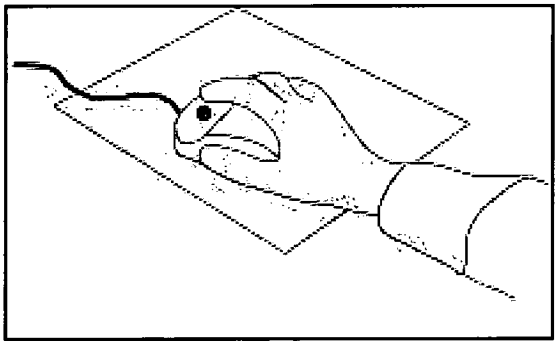

Figure 2.5 Simple reaction time

Body sway

Body sway (mm) was measured using a sway-meter to measure body displacement at the waist level as the participants stood as still as possible on a medium-density foam rubber mat (15 cm thick) for 30 seconds under two conditions - eyes open and eyes closed (Figure 2.6). The sway-meter consisted of a 40 cm rod attached at one end to the participant by a belt and to a pencil at the other end. The pencil rested on two millimetre graph paper to record the amount of sway during the 30 second period. Maximal medial-lateral and anterior-posterior sway (mm) were summed to calculate the final score for each condition.

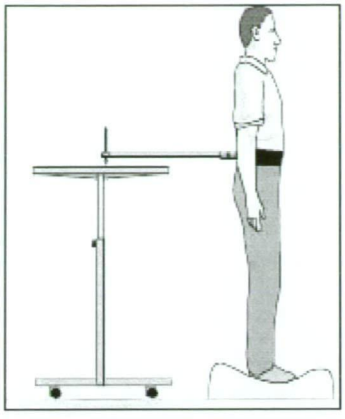

Figure 2.6 Body sway

Assessment of performance using the PPA

Better performance is indicated by larger scores of VCS and quadriceps strength and lower scores of proprioception, reaction time and body sway.

Reliability of the PPA

The reliability of these measures has been tested [7] and the results are summarised in Table 2.2.

Table 2.2 Test-retest reliability of sensorimotor measures

Measure	$ICC(2,1)^*$	(95% CI)
Visual contrast sensitivity	0.81†	(0.70,0.88)
Proprioception	0.50†	(0.15,0.74)
Maximal quadriceps strength	0.97†	(0.93,0.98)
Reaction time	0.69†	(0.45,0.84)
Sway on foam eyes open	0.57‡	(0.30,0.76)
Sway on foam eyes closed	0.83‡	(0.69,0.91)

Note: ICC = intraclass correlation coefficient; CI=confidence interval.
*The $\boldsymbol{ICC(2,1)}$ is appropriate when the occasion (test or retest) is considered to be a random source of variation, and the intention is to use the measurements from a single occasion as the data for each subject in the main study.
†Test and retest conducted two weeks apart for 13 men and 18 women aged 76 to 87 years
‡Test and retest conducted two weeks apart for 13 men and 21 women aged 50 to 70 years

Lower relative reliability for measures of proprioception (ICC=0.50) and sway on foam eyes open (ICC=0.57) was reported compared to measures such as maximal quadriceps strength (ICC=0.97). The generally lower ICCs for these variables suggest they are measured with greater random error. In studies designed to estimate relationships of these variables with gait variables, the larger random error is likely to produce greater

attenuation of the estimated association requiring greater sample size in tests of statistical significance.

2.6 Collection of falls data

A fall was defined as 'an unexpected event in which the participant comes to rest on the ground, floor, or lower level' in accordance with the ProFaNE consensus statement [11]. Falls data were collected over a 12 month period. Participants were mailed a falls questionnaire (Appendix 2A) with a reply paid envelope every two months asking them about their falls history. To assist with this process, participants were provided with a falls calendar that they could retain and record falls as they occurred (Appendix 2B). Telephone calls were made to participants who did not return the questionnaires.

2.7 Data analysis

The methods of statistical analysis for each study are described in the relevant chapter.

2.8 Ethics

Ethics approval was obtained from the Southern Tasmanian Health and Medical Human Research Ethics Committee. All participants provided written informed consent.

2.9 Postscript

The method for collecting gait, sensorimotor and falls data has been described in this chapter. The reliability of measurement of the sensorimotor factors and of average measures of gait has been investigated by others. However there is little information on the reliability of gait variability measures or on how many walking trials are required to provide a summary measures that adequately represent gait patterns. These issues will be examined in the next chapter.

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Appendix 2A: Falls study follow-up questionnaire

FALLS STUDY FOLLOW-UP

1. HAVE YOU HAD ANY FALLS IN THE MONTHS OF _____?

- o I have not fallen
- o Once
- o Twice
- o Three or more times

If you have had <u>no falls</u> please stop here, otherwise please continue

---

2. HOW DID YOU FALL? (Tick more than one if necessary)

- o I tripped
- o I slipped
- o I lost my balance
- o My legs gave way
- o I felt faint
- o I felt giddy / dizzy
- o Other, please specify

3. AS A RESULT OF THIS FALL OR FALLS DID YOU SUFFER ANY INJURIES?

- o Yes
- o No

4. IF YES WHAT TYPE OF INJURIES DID YOU SUFFER?

- o Bruises
- o Cuts/grazes
- o Broken wrist
- o Broken hip
- o Broken ribs
- o Back pain
- o Other, please specify

Thank you very much for your co-operation. Please return it to us by using the enclosed envelope.

Acknowledgement: Modified and used with permission from Professor Stephen Lord (Prince of Wales Medical Research Institute, Sydney, Australia)

Appendix 2B: Falls calendar

FALLS CALENDAR

You will be sent a questionnaire every two months regarding your falls history.

This calendar will help you remember any falls.

Keep it in a place that will remind you to fill it in – like on the fridge.

Each month, please tick a box if you have a fall. If you do not fall, please circle 'No Falls' at the end of that month.

At the end of twelve months you will be asked to return this calendar with your last falls questionnaire, therefore please keep this calendar in a safe place.

For this study a fall is defined as any occasion on which you find yourself unintentionally on the floor, ground or other lower surface, regardless of whether you sustain an injury.

JANUARY Falls ☐ ☐ ☐ ☐ ☐ No Falls	FEBRUARY Falls ☐ ☐ ☐ ☐ ☐ No Falls	MARCH Falls ☐ ☐ ☐ ☐ ☐ No falls
APRIL Falls ☐ ☐ ☐ ☐ ☐ No Falls	MAY Falls ☐ ☐ ☐ ☐ ☐ No falls	JUNE Falls ☐ ☐ ☐ ☐ ☐ No falls
JULY Falls ☐ ☐ ☐ ☐ ☐ No Falls	AUGUST Falls ☐ ☐ ☐ ☐ ☐ No Falls	SEPTEMBER Falls ☐ ☐ ☐ ☐ ☐ No falls
OCTOBER Falls ☐ ☐ ☐ ☐ ☐ No Falls	NOVEMBER Falls ☐ ☐ ☐ ☐ ☐ No Falls	DECEMBER Falls ☐ ☐ ☐ ☐ ☐ No Falls

Chapter 3: Issues in the measurement of the gait parameters

3.1 Preface

The previous chapter described the materials and methods that were used to measure gait and sensorimotor function in the studies reported in this thesis. This chapter examines two issues in relation to the measurement of gait. The first issue was to determine how many walks on the *GaitRite* mat are required to provide sufficient data to represent the gait patterns of participants. The second issue was to investigate measurement reliability. There have been a number of studies examining the test-retest reliability of average measures of gait, but only two studies to our knowledge have examined the reliability of gait variability measures. This chapter will investigate these two issues for both average measures of gait and gait variability.

3.2 Introduction

Temporal and spatial gait measures are widely used to assess a person's walking performance and to objectively measure gait change over time. The development of computerised walkways has meant that both temporal and spatial dimensions of gait can be measured quickly and easily by portable measurement systems. This has lead to their increased use in research and clinical practice.

Although a number of previous studies [1-6] have measured average measures of gait and gait variability with a computerised walkway using two or three walks, justification of the selected number of walks in the associated summary measures has not been provided. In the absence of such investigations, there has been no evidence base for recommendations for a minimum number of trials. Standardisation of methodology is critical to allow valid comparisons between studies.

To be useful, measurements of gait ideally should be free from systematic error and relatively free from random error. Systematic error is bias in a measurement that is constant or proportional to the true value and is in a predictable direction. For this reason, systematic error cannot be discovered on repetition of measurements. Random error is an unpredictable fluctuation in a measurement. In addition to inherent variability within individuals, random

error can be attributed to the testing procedure or the measuring instrument. By repeating a measurement, an assessment of reliability or reproducibility can be made. This refers to the extent to which the measurements are free of random error [7].

A number of studies have examined the reliability of the computerised *GaitRite* walkway for recording average measures of gait in both younger [2, 8] and older adults [2, 5, 9]. Studies of older adults have reported high reliability over intervals of one to two weeks for gait speed, step length and step time. Intraclass correlation coefficients (ICC) have ranged between 0.82 and 0.97 for these gait measures [2, 5, 9]. The reliability of double support phase (DSP) was reported to be high (ICC=0.93) in a sample of healthy adults aged 19-59 years (mean age 34 years) measured one week apart [8]. However, reliability for step width is reportedly lower (ICCs between 0.49 and 0.80) [2, 5, 9]. It has been suggested that the lower reliability for step width may be due either to the spatial resolution limitations of the *GaitRite* walkway or to the inherent variability in participants [2].

There are only two studies to our knowledge that have investigated the reliability of gait variability measures on a computerised mat [5, 10]. In the study by Brach et al. [5], men (n=219) and women (n=339) aged 65 years or older completed four walks on a four metre GaitMat II computerised mat within the same session. Test-retest reliability, calculated by combining the first two walks and the last two walks, was described as fair to good for step length variability (ICC=0.50) and stance time variability (ICC=0.63) and only marginal for step width variability (ICC=0.40). The same study also calculated reliability for single walks. Reliability was lower when using the single walks for step length variability (ICC=0.48), stance time variability (ICC=0.37) and step width variability (ICC=0.22) compared to using the two walks combined. Because reliability was only modest, the authors concluded that a greater number of walks may be required to improve reliability, but that participant fatigue must also be considered. Najafi et al. [10] also tested the reliability of two combined walks tested 10-15 minutes apart for men (n=9) and women (n=18) aged 70 years or older. The test-retest reliability for variability in stride velocity (ICC=0.37) and stride time (ICC=0.42), were described as poor. These studies of gait variability were limited because they were restricted to a maximum of four walks conducted within the same session, and did not consider the issue of temporal stability when walks are repeated after an intervening period of time.

The aims of this study were to (i) determine how many walks are required to adequately represent gait patterns measured using the *GaitRite* mat, and to (ii) examine the test-retest reliability of gait and gait variability, measured with six walks, over a one week period.

3.3 Methods

Study of the number of walks needed

Participants

The first 367 participants from the Tasmanian Study of Cognition and Gait (TASCOG) to complete six walks on the *GaitRite* walkway were included in this study. TASCOG participants (aged 60-86 years) were residents of southern Tasmania who were selected from the Tasmanian electoral roll in age- and sex-stratified random sampling. Participants were included if they were able to walk without a gait aid and able to follow instructions in English. Participants were excluded if they resided in a nursing home or if they had any contraindications to magnetic resonance imaging (MRI), which was a procedural requirement for the TASCOG study. The Southern Tasmanian Health and Medical Human Research Ethics Committee approved this study and written consent was obtained from all participants.

Gait Analysis

Measurements of step time, step length, DSP and step width and the variability of step time, step length, DSP and step width were made using protocols described elsewhere (Chapter 2). For each walk, the mean and standard deviation (SD) of each gait measure was calculated. To investigate variability between measurements, six walking trials were conducted. This number was considered to be the maximum that was feasible in terms of participant fatigue and burden. Gait speed and cadence were not included because, using the *GaitRite* software, measurements of these variables are available only as the average of all six walks.

Other measures

Information was collected regarding age and self-reported history of lower limb arthritis, diabetes, stroke, hypertension, Parkinson's disease and falls during the previous 12 months. Height (cm) was measured using a Leicester height measure (Invicta, Leicester, UK) and weight (kg) was measured using a Heine Portable Professional Adult Scale 737 (Heine, New Hampshire, USA).

Statistical Analysis

The number of walking trials required to obtain a mean value that was sufficiently representative of the mean of all six walks was assessed by calculating and comparing the mean and SD of each gait measure, and by calculating and comparing ICCs. The ICC was estimated firstly between the mean of the first walk and the mean of all six walks. Then the mean of the first two walks was calculated and the ICC between the two-walk mean and the six-walk mean was estimated. This process was continued using the mean of the first three walks, the mean of the first four walks and finally the mean of the first five walks, with comparison in each case against the six-walk mean. The results were then inspected to identify how many walks were required to obtain a mean that was representative of the mean of all six walks. The mean of all six walks was the best estimate available of the true gait pattern of participants.

The $ICC\ (1,1)$ form of the ICC was used because this study was considered to be a simple replication study of the type described by Shrout and Fleiss [11]. The formula for the $ICC\ (1,1)$ is:

$$ICC(1,1) = \frac{BMS - WMS}{BMS + (k-1)WMS}$$

where BMS is the between-subject mean square and WMS is the within-subject mean square from a one-way analysis of variance, and k is the number of replications (here $k = 2$, being the two means used in the comparison). This is appropriate for a one-way comparison of two measurements (here two summary measures each representing a different collection of walks from the entire set of six walking trials) in which the walking trials are considered to be a random effect and no attempt is made to partition the error between that associated with forming two collections of trials and residual error.

Test-retest study

Participants

Participants were 16 volunteers aged 60-86 years (6 men, 10 women) recruited from friends and family of staff at the Menzies Research Institute. Ethics approval for this study was gained from the Southern Tasmanian Health and Medical Human Research Ethics Committee, and informed consent was obtained from all participants.

Gait Analysis

Gait measures - gait speed, step length, cadence, DSP, step width and variability in step length, step time, DSP and step width - were measured using protocols described elsewhere (Chapter 2). The procedure was repeated one week later on the same day of the week and at the same time of the day.

Other measures

The previously described information regarding participant self-reported history of medical conditions and falls, and measures of height and weight were also collected for this study.

Statistical Analysis

Differences in gait measures from week one to week two were compared using a series of paired t-tests. The $ICC(1,1)$ form of the ICC was used because this study also was considered to be a simple replication study of the type described by Shrout and Fleiss [11]. The formula for the $ICC\ (1,1)$ was given previously. The choice of this form of the ICC was based on three considerations. Firstly, the reliability of a single summary measure (the mean of six summary walks) of each gait characteristic was being assessed. For gait speed and cadence, this was all that was possible because the software provides measurements of these only as the average of all completed walks. Secondly, the measurements were made under identical conditions and just one week apart. The variation from occasion (test) to occasion (retest) within individuals could not be attributed to different equipment (the same *GaitRite* mat was used), or to different measurers (the same person took the measurements on each occasion using the same protocols), or to any other difference apart from the occasion (test, retest). If occasion is regarded as a source of variation, the within-person error can be partitioned between error due to occasion and residual error, and the choice of ICC lies between the $ICC\ (2,1)$ that models occasion as a random source of variation (referred to by Shrout and Fleiss as a Case 2 study [11]), and the $ICC\ (3,1)$ that models occasion as a fixed source of variation (referred to by Shrout and Fleiss as a Case 3 study [11]). Whilst Shrout and Fleiss [11] warn against the misuse of the $ICC\ (1,1)$ for data from a Case 2 or Case 3 study, because the $ICC\ (1,1)$ will on average give smaller values than the $ICC(2,1)$ or $ICC(3,1)$ and the true correlation would be underestimated, the conservative stance of not recognising occasion as a source of variation was considered to be most appropriate in the circumstances of this study. Thirdly, some gait researchers (see Van Uden and Besser [8]) have used a form of the ICC that is appropriate for a replication study in which the average of

the replicates is to be used in the analysis of the main study. This gives rise to the $ICC(1,k)$, $ICC(2,k)$ and $ICC(3,k)$ forms of the $ICC(1,1)$, $ICC(2,1)$ and $ICC(3,1)$ respectively, where k is the number of replications. In a simple replication study with $k = 2$ replicates, such as this one, the $ICC(1,2)$ would be used in place of the ICC $(1,1)$ if the mean of the test and retest values was to be used in analyses of the main study. This was not the intention in the studies that follow in subsequent chapters, and it was not possible in any case because no retesting was done of the participants in those studies.

We further investigated the effect of variability in the gait measures from week one to week two by estimating an index of potential for misclassification in a main study in which gait variables were divided into quarters for analytical purposes (as was done in the study of gait and risk of falls in Chapter 8 of this thesis). This was done by calculating the percentage of participants in the main study who would be re-classified in a different quarter if their gait measurement changed as much on a second occasion as did the measurements on average in the test-retest study. For a typical example of a "main study", we used the data from the first study reported in this chapter (the study of the number of walks needed).

3.4 Results

Study of the number of walks needed

The mean age of the sample was 72.2 (standard deviation (SD) 7.1) years. Men comprised of 55.9% (205/367) of the sample (Table 3.1). On average, 27.9 (SD 5.0) steps were collected per participant.

Table 3.1 Characteristics of the sample (n=367)

Age, mean (SD)	72.2 (7.1)
Sex (Male), n (%)	205 (55.9)
Height in cm, mean (SD)	166.6 (8.8)
Weight in kg, mean (SD)	77.4 (15.2)
Lower limb arthritis, n (%)	164 (44.9)
Falls in previous 12 months, n (%)	62 (16.9)
Hypertension, n (%)	189 (51.5)
Diabetes, n (%)	46 (12.5)
Stroke, n (%)	29 (7.9)
Parkinson's Disease, n (%)	2 (0.5)

Notes: SD=standard deviation

The mean and standard deviation of each walk are presented in Table 3.2 for each gait measure. From walk one to walk four, mean step length slightly increased, and the mean of the other gait measures (step time, DSP and step width) slightly decreased, with the greatest change occurring between the first and second walks. The inter-individual (between-subject) standard deviation (SD) fluctuated showing no clear trend. Mean intra-individual (within-subject) variability of the gait measures in most cases decreased with successive walks from walk one to walk four, and the between-subject SD of the intra-individual gait variability measures tended to fluctuate without clear trend. The ratio of SD to the mean (coefficient of variation) was much higher for variability measures than for average measures of gait, ranging from 9% to 35% for average measures of gait, and from 50% to 71% for the variability measures (data not shown).

The results of combining successive walks with all previous walks are shown in Table 3.3. Reflecting the influence of the discrepant first measurements of gait and the trends to less exceptional values with subsequent walks, the means of combinations of walks increased (step length) or decreased (step time, DSP, step width) as the combination of walks was expanded to include walks with more uniform values. The mean continued to adjust even as the sixth walk was added, however. Reflecting the trends to decreased variability in each successive walk, the average of gait variability measures tended to increase as further walks with more divergent average values were added to the combination.

For average measures of gait, the ICC between the mean of successively larger collections of walks and the ICC of all six walks reached 0.98 or 0.99 when the first two or three walks were averaged. For gait variability measures, the ICC continued to increase as successively more walks were included. Except for step width variability, the ICC reached 0.96 or greater between the mean of the first five walks and the mean of all six walks. For step width variability the ICC between the mean of five walks and the mean of six walks only reached 0.89.

Test-retest study

Table 3.4 describes the characteristics of the participants in the test-retest study. The average number of steps collected was 26.38 (SD 4.52). The sample was similar in age to the sample used in the study of number of walks needed that was reported previously, but males were not as well represented and participants were slightly healthier in terms of self reported lower limb arthritis, hypertension, diabetes and stroke.

Table 3.2 Inter-individual (between-subject) average and standard deviation of each gait measure and each intra-individual (within-subject) gait variability measure for each walking trial separately (n=367 participants)

	Walk number					
	1	2	3	4	5	6
Step length (cm)						
Mean	60.21	61.42	61.25	62.08	61.56	62.12
SD	9.34	9.25	9.21	9.20	9.27	9.36
Step time (ms)						
Mean	556.30	548.80	546.79	542.52	543.13	542.64
SD	53.51	53.20	53.14	53.81	54.10	53.49
Double support phase (ms)						
Mean	264.34	254.83	253.70	249.20	250.57	247.50
SD	59.49	57.68	58.48	57.07	58.44	57.75
Step width (cm)						
Mean	10.32	9.96	9.96	9.80	9.96	9.81
SD	3.32	3.25	3.22	3.21	3.31	3.50
Step length variability (cm)						
Mean	2.33	2.25	2.22	2.23	2.12	2.15
SD	1.28	1.22	1.21	1.15	1.06	1.20
Step time variability (ms)						
Mean	19.45	19.10	18.30	17.47	17.52	17.46
SD	13.47	12.64	13.50	11.72	12.10	12.43
Double support phase variability (ms)						
Mean	14.68	13.35	14.42	13.44	14.01	13.08
SD	8.43	8.26	9.93	7.88	9.81	8.82
Step width variability (cm)						
Mean	1.73	1.72	1.70	1.54	1.61	1.64
SD	0.97	1.04	1.03	0.92	0.90	0.91

Notes: SD=standard deviation

Table 3.3 Inter-individual (between-subject) mean and standard deviation of each gait measure and each intra-individual (within-subject) gait variability measure for combinations of walking trials (n=367 participants)

	Walks included in collection					
	1	1,2	1,2,3	1,2,3,4	1,2,3,4,5	All 6
Step length (cm)						
Mean (SD)	60.21 (9.34)	60.78 (9.23)	60.91 (9.18)	61.18 (9.13)	61.25 (9.13)	61.38 (9.14)
ICC (95% CI)	0.97 (0.97,0.98)	0.99 (0.99,0.99)	0.99 (0.99, 1.00)	1.00	1.00	1.00
Step time (ms)						
Mean (SD)	556.30 (53.51)	552.60 (52.45)	550.68 (52.26)	548.67 (52.30)	547.58 (52.33)	546.80 (52.31)
ICC (95% CI)	0.93 (0.92,0.95)	0.98 (0.97,0.98)	0.99 (0.99,0.99)	1.00	1.00	1.00
Double support time (ms)						
Mean (SD)	264.34 (59.49)	259.62 (57.25)	257.77 (57.02)	255.68 (56.42)	254.70 (56.36)	253.55 (56.20)
ICC (95% CI)	0.93 (0.92,0.95)	0.98 (0.97,0.98)	0.99 (0.99,0.99)	1.00	1.00	1.00
Step width (cm)						
Mean (SD)	10.32 (3.32)	10.14 (3.10)	10.09 (3.02)	10.02 (2.96)	10.01 (2.96)	9.97 (2.98)
ICC (95% CI)	0.89 (0.87,0.91)	0.95 (0.94, 0.96)	0.98 (0.97, 0.98)	0.99 (0.99,0.99)	1.00	1.00
Step length variability (cm)						
Mean	2.33 (1.28)	2.59 (1.07)	2.61 (0.98)	2.69 (1.03)	2.67 (0.96)	2.70 (0.93)
ICC (95% CI)	0.51 (0.44,0.59)	0.74 (0.69,0.79)	0.83 (0.79,0.86)	0.94 (0.93,0.95)	0.97 (0.96,0.98)	1.00
Step time variability (ms)						
Mean	19.45 (13.47)	21.36 (12.14)	21.42 (11.65)	21.53 (11.16)	21.58 (10.78)	21.45 (10.50)
ICC (95% CI)	0.71 (0.66,0.76)	0.87 (0.84,0.89)	0.92 (0.91, 0.94)	0.96 (0.95, 0.97)	0.98 (0.98,0.99)	1.00
DSP variability (ms)						
Mean	14.68 (8.43)	18.11 (8.50)	19.20 (8.41)	19.82 (8.45)	20.12 (8.13)	20.04 (7.76)
ICC (95% CI)	0.21 (0.11,0.30)	0.64 (0.58,0.70)	0.83 (0.80,0.86)	0.91 (0.89,0.93)	0.96 (0.95, 0.97)	1.00
Step width variability (cm)						
Mean (SD)	1.73 (0.97)	2.02 (0.88)	2.08 (0.82)	2.11 (0.73)	2.11 (0.68)	2.12 (0.68)
ICC	0.30 (0.20, 0.39)	0.64 (0.58,0.70)	0.78 (0.74,0.81)	0.85 (0.82,0.88)	0.89 (0.86,0.91)	1.00

Notes: SD=standard deviation, ICC=intraclass correlation coefficient; CI=confidence intervals

Mean values of the gait and gait variability measures in each session are shown in Table 3.5, together with the difference in means. Our results are consistent with a pattern of performance whereby participants walked slightly faster on the second occasion. Other than for step width (p=0.01), there were no significant differences between mean values of gait or gait variability measures between sessions. The differences would have been significant in a larger sample, however. For example, the estimated numbers of participants to find a significant difference were approximately n=56 for gait speed, n=435 for cadence, n=36 for step length, n=120 for DSP, n=30 for step length variability, n=35,384 for step time variability, n=150 for DSP variability and n=46 for step width variability. These sample sizes were estimated by replicating the data until the differences became statistically significant and interpolating to find the minimum number at which p=0.05.

Table 3.4 Characteristics of the sample (n=16)

Age, mean (SD)	70.0 (8.7)
Sex (Male), n (%)	6 (37.5)
Height in cm, mean (SD)	165.5 (10.3)
Weight in kg, mean (SD)	71.7 (16.7)
Lower limb arthritis, n (%)	2 (12.5)
Falls in previous 12 months, n (%)	2 (12.5)
Hypertension, n (%)	7 (43.8)
Diabetes	0 (0)
Stroke, n (%)	0 (0)
Parkinson's disease, n (%)	0 (0)

Notes: SD=standard deviation; cm=centimetres; kg=kilograms

Tests of the relative reliability of the gait and gait variability measures are reported in Table 3.6 as ICCs. The ICCs were generally lower for the variability measures, particularly for DSP and step width variability where the ICCs did not exceed 0.50. Whilst the magnitude of the ICC reflects the relative amounts of within-subject and between-subject variation in the data, and will tend to be larger in datasets with greater between-person variation (such as when persons of a wide range of ages are included in the study), a general guideline is that correlations of 0.50 to 0.75 indicate a moderate to good relationship, and those over 0.75 indicate a very good to excellent relationship [12].

Table 3.5 Mean (SD) values of each gait measure and each intra-individual (within-subject) gait variability measure for the two sessions

Gait variable	Session 1		Session 2		Difference	
	Mean	SD	Mean	SD	Mean	SD
Gait speed (cm/sec)	127.58	16.88	129.70	20.88	2.13	7.61
Step length (cm)	65.99	7.59	66.76	8.31	0.77	2.30
Cadence (steps/min)	116.08	8.84	116.41	10.87	0.34	3.68
DSP (ms)	216.75	38.21	215.53	40.32	-1.21	10.51
Step width (cm)	8.29	2.84	8.69	2.95	0.40*	0.57
Step length variability (cm)	2.12	0.60	2.31	0.55	0.20	0.50
Step time variability (ms)	15.42	4.57	15.46	4.52	0.04	4.22
DSP variability (ms)	17.72	3.54	17.02	3.43	-0.70	4.40
Step width variability (cm)	1.87	0.46	1.70	0.53	-0.17	0.58

Notes: SD=standard deviation; cm=centimetres; ms=milliseconds; DSP = double support phase; *$p<0.05$

The percentage of participants in the trial number study who would have been re-classified into another quarter, had their gait measures changed on a second occasion by the mean difference reported in Table 3.6, were relatively high for step length variability and step width variability, but less than 10% for cadence and step time variability.

Table 3.6 Test-retest reliability for each gait measure and each intra-individual (within-subject) gait variability measure

Gait Variable	$ICC(1,1)$	(95% CI) n=16	Potential for misclassification n (%) n=367
Gait speed (cm/sec)	0.92	(0.79,0.97)	39 (10.6)
Step length (cm)	0.96	(0.88, 0.98)	42 (11.4)
Cadence (steps/min)	0.93	(0.83, 0.98)	19 (5.2)
DSP (ms)	0.97	(0.91,0.99)	54 (14.7)
Step width (cm)	0.97	(0.92, 0.99)	58 (15.8)
Step length variability (cm)	0.59	(0.17,0.83)	113 (30.8)
Step time variability (ms)	0.59	(0.16,0.83)	3 (0.8)
DSP variability (ms)	0.22	(0.00,0.63)	54 (14.7)
Step width variability(cm)	0.30	(0.00,0.68)	125 (34.1)

Notes: ICC=intraclass correlation coefficient, CI=confidence interval; cm=centimetres; ms=milliseconds; DSP=double support phase

3.5 Discussion

There were two issues that were examined in this study. The first issue was to determine how many trials were needed on a *GaitRite* mat to provide the most accurate summary measure of gait and gait variability measures, and the second issue was to examine test-retest reliability of these measures over a one week period.

The number of trials needed differed depending on the use of the gait measures. For average measures of gait, if the focus is on mean values, the influence of the first discrepant measurement of the mean was such that a greater number of measurements were required to stabilise the gait measure (at least six trials). The results were consistent with participants becoming slightly faster (increased step length, decreased step time and decreased DSP) at least until the fourth trial. Although the most discrepant measurements occurred on the first trial, those on subsequent measurements became increasingly more uniform. This was perhaps due to increased familiarity or confidence with the task at hand, even though all participants completed two practice trials before measurements were recorded. If ranking of participants is important in analyses of average measures of gait, as it is in studies of the association of gait measures with age and other study factors, the ICCs suggested that the mean of the first three or four walks is adequate to represent all six walks. For the gait variability measures the overall mean of each generally increased as the different values of each trial were combined together, but the change was minor after the first four walks were taken into account. Reflecting the relatively large within person variation, as evidenced by the coefficients of variation of the gait variability measures, the gains from proceeding to a fifth or sixth trial lay in the improved stability of ranking of participants for an association study as evidenced by the improvements in the ICCs.

One factor that was a major consideration in the design of these studies was the maximum number of walking trials for participants to complete. We settled on six trials without a great deal of evidence to guide us. Further research is required to determine if a greater number of trials improves the representation of these gait measures.

In the test-retest study, stability of measurements was assessed over a one week period. The differences in mean values for our sample were small in relation to their standard deviations, and only that for step width reached statistical significance, but the differences for several others (gait speed, step length, step length variability and step width variability) may have been statistically significant in a larger study with at least 50 or 60 participants. The differences that were found do not appear to be of clinical significance [13, 14], but

they are sufficient to result in misclassification of substantial numbers of participants in analytical investigations for which the continuous measurements are divided into quarters (as they are in the analyses of chapters that follow). Assessment of relative reliability suggested that ranking of individuals changed markedly for the variability measures, in particular for step width and DSP variability. As indicated by the high test-retest ICCs, the ranking of average measures of gait were consistent over the one week period.

The results of this study are consistent with those of previous test-retest studies that have found gait speed, step length, cadence and DSP – measured on a *GaitRite* mat – to have ICCs greater than 0.80 [2, 5, 9]. Our ICC of 0.97 for step width was higher than those reported in a study by Menz et al. (ICC range 0.49-0.56) [2]. This may have been due to the greater number of walks used in our study (six walks compared to only three walks in that study) or the age of their participants because greater age is associated with greater within-subject variability in step width (see Chapter 5 of this thesis).

Our results for gait variability measures are in agreement with those of a previous study [5] that reported step length variability was more consistent than step width variability when measured on a GaitMat II electronic walkway. Our reliability coefficients for step length and step width variability, measured over a period of one week, were similar to those of that previous study in which reliability was assessed within a single session. This comparison is not conclusive because the type of ICC that was used in that study was not stated and the different formula give different results. It should be noted in this regard that the $ICC(1,1)$ that was used in this study tends to give lesser values than the $ICC(2,1)$ and $ICC(3,1)$ formulae that may have been used [11]. In comparing results for step width variability, it should also be noted that a slightly different definition of this variable was used. Our ICC of 0.59 for step time variability was higher than that reported for stride time variability (one stride equals two steps) in a study by Najafi et al.($ICC(1,1) = 0.42$) [10]. This may have been due to the greater number of walks used in our study (six walks compared to only two in that study).

The lower relative reliability for step width and DSP variability than for step length variability, in both this and a previous study [5], may be because these measures have greater inherent variability for older people [15]. The lower reliability for step width may be due also to the lower spatial resolution of the gait mat. Sensors are placed 1.27cm apart and this could lead to errors in measurements of step width that are only around 10cm themselves [2]. For studies investigating associations between variables, the presence of

random error in these gait measures increases the sample size needed to detect associations.

Summary

The minimum number of walks that are required to adequately represent measurements of gait and gait variability was investigated in this chapter. It appears that at least six trials on a 4.6 metre *GaitRite* mat are required if the purpose is to present mean values of average measures of gait, and at least four trials are required to measure variability in gait. For analytical studies of association of these gait measures with other factors (as in the studies of this thesis) for which relative stability in ranking of participants is important, three to four trials are required to represent average measures of gait and at least six trials are required to represent measures of gait variability. Overall it seems necessary, and feasible in terms of participant burden, to require at least six trials.

The results from the test-retest study showed high levels of consistency for average measures of gait over the one week period, but less so for gait variability measures, particularly DSP and step width variability.

3.6 Postscript

Six trials will be available to be used in analyses of gait and gait variability in subsequent chapters. This may be adequate to detect associations of average gait measures with study factors such as age and sensorimotor function, but the prospects for detecting associations with gait variability measures with these factors are less certain. The test-retest study results suggest that for gait variability measures considerable random error remains even after averaging six measurements, and this information will need to be considered when interpreting the size and statistical significance of associations estimated in subsequent chapters.

Having completed these preliminary investigations, the following chapter will examine the association of age with temporal and spatial gait measures. Age-related decline in mobility has serious consequences for the individuals involved and for society. Research such as this into patterns of age-related decline offers prospects for slowing its development and reducing its impact.

3.7 References

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Chapter 4: Sex modifies the relationship between age and gait - A population-based study of older adults

4.1 Preface

The previous chapter reported on studies investigating how many walks are required to adequately represent measurements of gait measures on a 4.6 metre *GaitRite* mat and the test-retest reliability of these measures over a one week period. For analytical studies of the association of gait measures with study factors such as age, at least three to four trials were found to be necessary for average measures of gait. Six trials are available for the studies reported in this thesis. The test-retest reliability of average measures of gait was found to be high. These results suggest that error in measurement of the average gait measures will not be a major contribution factor if associations with relevant study factors are unable to be discerned.

Understanding which gait measures are age-related may lead to more specific interventions to help maintain walking speed and independence. In this chapter the associations between age and a number of temporal and spatial gait measures are examined in a population-based sample of 223 community dwelling older people. The associations are also examined for differences between the sexes.

The results of this chapter and Appendix 4B, which considers in detail the issue of outliers in the results for women, have both been published [1, 2]. Appendix 4A provides results on another gait measure, double support phase measured in seconds, that was not included in the published papers because it is highly correlated with (provides essentially the same information as) double support phase measured as a percentage.

4.2 Introduction

Adequate mobility is essential for older adults to maintain an independent and active lifestyle. The prevalence of abnormal gait has been reported to be as high as 35% in adults > 70 years [3]. Gait problems are associated with falls [4-7], which can lead to hospitalisation [7], institutionalisation, and increased mortality [3]. A better understanding of how gait is affected by advancing age is required to assist in targeting appropriate age groups for interventions to prevent falls and loss of independence.

Previous studies describe a decrease in speed [8-19] and step length [8, 10-15, 17, 18, 20] with age, but disagree on its effect on cadence [8, 11-18, 20]. Few studies, however, have investigated the relationship between age and other gait variables, such as step width and double support phase (DSP) [8, 10, 13, 21-24]. It is also unclear whether the effect of increasing age on gait variables is similar in men and women. Although previous data indicate that older women walk at a slower speed, take shorter steps, and have a faster cadence than men [25], it is unknown whether these differences are consistent across the older age range.

Prior studies of ageing and gait have compared only young and older adults [8, 10, 14, 15, 20, 23, 25] in small samples of healthy volunteers [8-24], which limit their generalisability and usefulness in understanding how gait changes across the continuum of older age. There are very few population-based studies of age and gait [4, 6, 25-29], with even fewer examining more than one gait variable in both men and women [25, 28]. Therefore, the aims of this study are: (i) to describe the associations of age with a range of temporal and spatial gait variables in a randomly selected older population-based sample and (ii) to investigate whether such associations differ in men and women.

4.3 Methods

Study Participants

Participants aged between 60 and 86 years were randomly selected from a comprehensive list of residents, the Southern Tasmanian electoral roll, into the Tasmanian Study of Cognition and Gait (TASCOG) (n=223). TASCOG is a population-based study of the neural correlates of gait, balance, and cognition in older people. Southern Tasmania has a total population of 239,444 people including 46,159 persons aged at least 60 years [30], predominantly Caucasians of a northern European ancestry. Participants were excluded if they lived in a nursing home or were unable to walk without a gait aid. The Southern Tasmanian Health and Medical Human Research Ethics Committee approved this study, and written consent was obtained from all participants.

Gait Analysis

Gait variables (speed, cadence, step length, step width and DSP) were measured using the 4.6 metre *GAITRite* system (CIR Systems Inc., Clifton, NJ). The *GAITRite* is a portable carpet walkway with embedded pressure sensors that collect gait data electronically as the participant walks over the carpet. The *GAITRite* system has demonstrated high concurrent validity relative to a 'gold standard' three-dimensional motion analysis system [31] and has

excellent test-retest reliability in older adults [32]. Participants started and finished walking two metres before and after the mat to allow for acceleration and deceleration. After two practice trials, participants performed six walks at their preferred speed, and gait measures were averaged over the six walks.

Results are presented for five gait variables (speed, cadence, step length, step width, and DSP (%)), but in exploratory data analyses we also examined DSP measured in seconds. Those results are not reported because DSP (secs) is highly correlated with DSP percentage (*The results for DSP (secs) are reported in Appendix 4A*).

Other Measurements

Height (cm), weight (kg) and self-reported history of lower limb arthritis, stroke, Parkinson's disease, diabetes mellitus and falls (in the preceding 12 months) were recorded using a standardised questionnaire. Nonresponders completed a brief phone interview providing some details about their medical history (diabetes mellitus and stroke) and history of falls in the previous 12 months.

Data Analysis

Chi-square and Student *t*-tests were used to compare gait variables between men and women (Table 4.1), Spearman correlation coefficients were used to measure the associations between gait variables (Table 4.2), analysis of variance methods were used for the analysis of age (Table 4.3), and linear regression was used to estimate the cross-sectional relationship between each gait variable and age (Table 4.4, Figure 4.1). To adjust for height and weight, linear terms for these covariates were added to the regression models. In the regression analysis for women, speed and step width were log transformed, and the square of age was added as an additional covariate to capture the remaining nonlinearity for each gait variable. Two younger, slow-paced women were excluded from analysis after examination for outliers because they were highly influential in producing an implausible inverted U shape in the relationship of speed with age *(For further information see Appendix 4B)*. For gait variables that varied nonlinearly with age, methods of calculus were used to estimate the turning points. Statistical interaction between age and sex was assessed by a test of significance of a $(Age \times Sex)$ product term for men, and by a partial F test [33] for the inclusion of two product terms $(Age \times Sex, Age^2 \times Sex)$ in the model for women. Similar methods were used to assess modification by height and weight. To investigate whether the findings were biased because participants tended to be younger

than non-participants, and with a lesser prevalence of self-reported falls, the regression analyses were repeated with participants weighted by the multiple $w_{ijk} = {}^{N_{ijk}}\!/_{n_{ijk}}$ where N_{ijk} represents the number of eligible participants (participants and nonparticipants) in a particular age (i), sex (j), and falls history (k) category, and n_{ijk} represents the number of participants in that category.

4.4 Results

The sample response proportion was 53.0 % (223/420). Non-responders were older (p<0.001) and reported falling less often in the previous 12 months (p<0.001), but did not differ by sex (p=0.84) or prevalence of stroke (p=0.20) or diabetes (p=0.28).

Demographic, clinical, and gait characteristics of the sample are provided in Table 4.1. Men had greater step length (p<0.001) and step width (p<0.001) than women, but had lower cadence (p<0.001) and DSP (p=0.02). A greater proportion of women than men reported falling in the preceding year (p=0.002).

Table 4.1 Sample characteristics (n=223)

Characteristic	Men (n=120)	Women (n=103)
Age, mean (SD)	72.9 (6.8)	72.4 (7.4)
Height in cm, mean (SD)*	172.1 (6.5)	159.2 (5.1)
Weight in kg, mean (SD)*	81.2 (13.0)	69.7 (13.6)
Gait Measures, mean (SD)		
Speed, cm/sec	113.83 (18.36)	109.26 (20.39)
Cadence, steps/min*	106.30 (8.45)	114.34 (10.96)
Step length, cm*	64.16 (7.94)	57.05 (7.63)
Step width, cm*	10.81 (2.93)	8.73 (2.69)
DSP, %‡	23.56 (3.11)	24.63 (3.83)
Medical history§		
Stroke, n (%)	8 (6.7)	8 (7.8)
Parkinson Disease, n (%)	1 (0.8)	0 (0.0)
Lower limb arthritis, n (%)	50 (41.7)	43 (41.7)
Diabetes mellitus, n (%)	14 (11.7)	9 (8.7)
Falls‖, n (%)†	14 (11.7)	29 (28.2)

Notes: *p<0.001; †p<0.01; ‡p<0.05;
SD=standard deviation; DSP=double support phase.
§ Self-reported; ‖ Previous 12 months.

Associations between gait variables are shown in Table 4.2.

Table 4.2 Correlations between gait variables in men and women (n=221)

	MEN				
WOMEN	Speed (cm/s)	Cadence (steps/sec)	Step length (cm)	Step width (cm)	DSP (%)
Speed, cm/s	-	*0.58**	*0.88**	*-0.22*‡	*-0.51**
Cadence, steps/min	0.76*	-	*0.18*	*-0.08*	*-0.20*‡
Step length, cm	0.92*	0.49*	-	*-0.23*‡	*-0.57**
Step width, cm	-0.31†	-0.14	-0.34*	-	*0.28*†
DSP, %	-0.71*	-0.43*	-0.73*	0.31†	

Notes: $^{*}p<0.001$; $^{†}p<0.01$; $^{‡}p<0.05$;
DSP=double support phase; – = the variables correlate perfectly.

The strongest associations were between speed and cadence, step length, and DSP for women and speed and step length for men. Speed and step length were negatively associated with age category in both men and women (Table 4.3). Cadence was negatively associated with age category only in women. DSP (in women) and step width (in men) showed positive associations with age category. Fitted regression curves were used to characterise the cross-sectional relationship between age and gait variables in men and women. In men, the relationships were linear, but in women the associations of age with speed (p=0.002), cadence (p=0.003), step length (p=0.07), step width (p=0.08), and DSP (p=0.01) were curvilinear (Figure 4.1). Peak speed, cadence, and step length were recorded by women aged 65.2 (standard error *SE* 3.1), 67.5 (*SE* 2.7) and 61.5 (*SE* 6.8) years respectively. Lowest step width and DSP were recorded by women aged 70.0 (*SE* 2.9) and 65.5 (*SE* 3.4) years respectively. Results of the multivariable linear regression of age with gait measures are shown in Table 4.4.

After adjusting for height and weight, age was significantly associated with all gait variables in men except cadence. In women, the strength of the association between age and gait variables varied across the study age range, with associations being strongest among the oldest women. Significant interactions were seen between age and sex for speed (p=0.04), cadence (p=0.01) and DSP (p=0.03). These associations and interactions remained significant after controlling for chronic disease. Repeating analyses with participants weighted for nonresponse confirmed that the curvilinear relationships persisted, and thus were not due to participating women being younger than non-participating women, or fewer of them having fallen.

Table 4.3 Univariable associations between age and gait measures (n=223)

Age group (years)	n	Speed (cm/sec)	Cadence (steps/min)	Step length (cm)	Step Width (cm)	DSP (%)
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Men						
60-64	15	126.33 (21.03)	109.57 (10.81)	68.98 (7.26)	10.84 (2.85)	23.15 (3.31)
65-69	28	120.62 (14.96)	106.88 (7.44)	67.68 (6.04)	9.56 (3.08)	23.33 (3.06)
70-74	27	113.69 (12.45)	105.62 (6.91)	64.72 (6.67)	10.56 (2.54)	22.88 (3.17)
75-79	26	108.60 (21.97)	106.15 (9.73)	61.03 (8.67)	11.90 (3.03)	24.50 (3.37)
80-86	24	103.94 (14.90)	104.49 (8.08)	59.80 (7.63)	11.35 (2.74)	23.85 (2.64)
Trend		-5.66	-0.99	-2.57	0.43	0.28
(95% CI)		(-7.97, -3.34)*	(-2.14, 0.17)	(-3.56, -1.58)*	(0.03, 0.82)‡	(-0.15, 0.70)
Women						
60-64	22	116.48 (17.01)	114.80 (8.61)	60.67 (5.96)	8.48 (2.71)	23.89 (4.24)
65-69	21	116.59 (15.46)	117.57 (6.62)	59.29 (5.46)	8.41 (1.98)	23.83 (2.97)
70-74	15	121.93 (19.17)	120.21 (10.60)	60.74 (6.53)	8.09 (1.97)	22.57 (2.73)
75-79	27	104.41 (16.41)	113.26 (8.27)	55.25 (7.00)	8.65 (2.63)	25.34 (3.46)
80-86	18	88.61 (19.43)	106.75 (12.17)	49.65 (7.86)	10.03 (3.68)	27.10 (4.32)
Trend		-6.47	-1.88	-2.51	0.30	0.76
(95% CI)		(-8.99, -3.96)*	(-3.20, -0.55)†	(-3.44, -1.58)*	(-0.07, 0.67)	(0.25, 1.27)†

Notes: *$p<0.001$; †$p<0.01$; ‡$p<0.05$;
SD= standard deviation; SE= standard error; CI=confidence interval; DSP=double support phase.

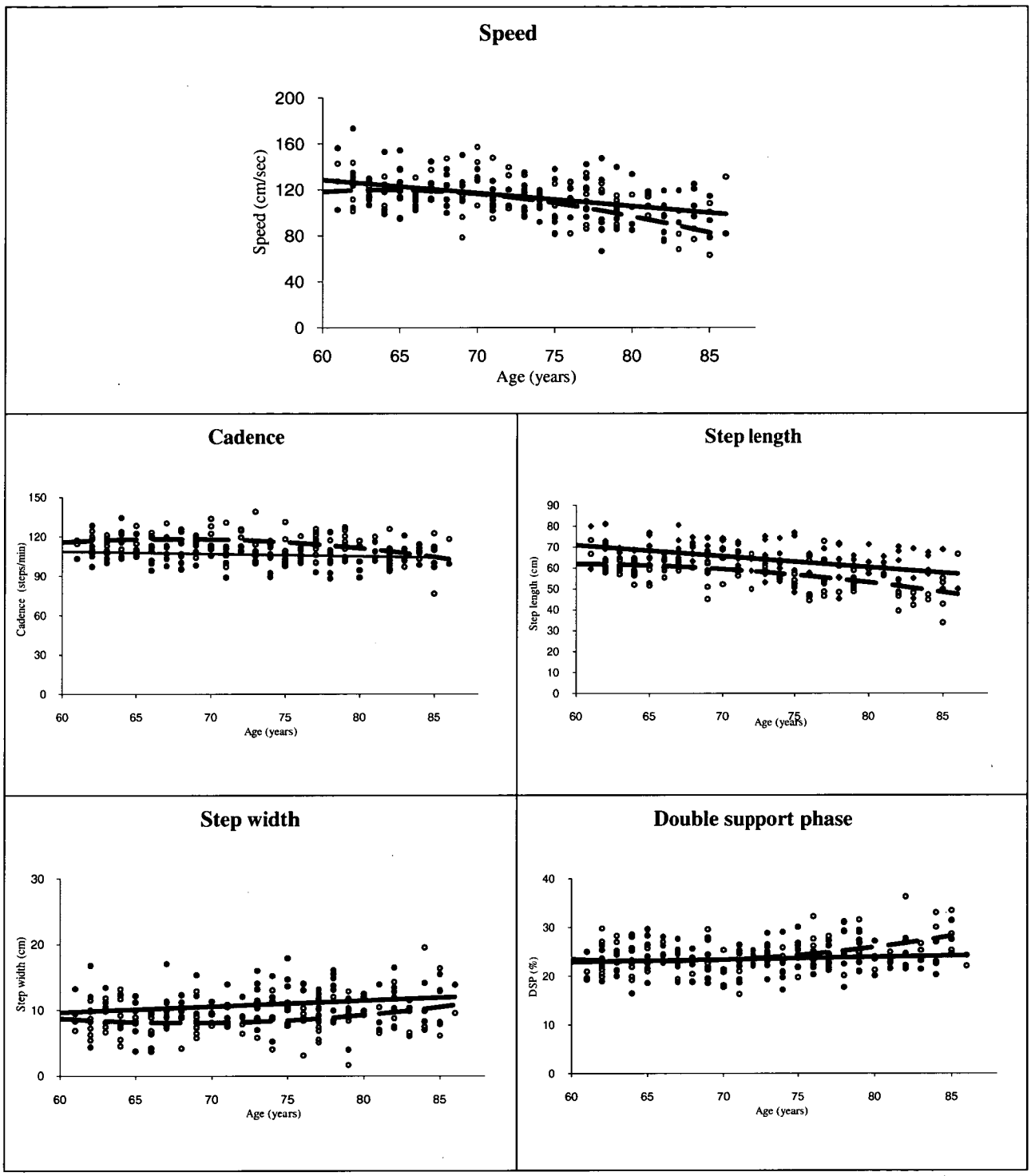

Figure 4.1: Scatter plots and fitted regression lines of the relationship between age and each gait measure (n = 221).

Notes: ● = Men; o = Women; —— = line of best fit for men; – – – = line of best fit for women. DSP=double support phase.

Table 4.4 Cross-sectional effect of an additional year of age on gait measures (n=221)

Gait variable	Regression coefficients for age (β): Unadjusted β (95% CI)	Height and Weight Adjusted β (95% CI)
Men		
Speed (cm/sec)	-1.14 (-1.58, -0.69)*	-1.14 (-1.61, -0.67)*
Cadence (steps/min)	-0.18 (-0.40, 0.05)	-0.19 (-0.43, 0.04)
Step length (cm)	-0.53 (-0.72, -0.34)*	-0.53 (-0.71, -0.34)*
Step width (cm)	0.09 (0.01, 0.17)‡	0.13 (0.06, 0.21)†
DSP (%)	0.05 (-0.03, 0.14)	0.11 (0.03, 0.19)†
Women		
Speed (cm/sec)§		
- at age 65 years	-0.38 (-1.53, 0.77)	-0.20 (-1.31, 0.90)
- at age 75 years	-1.89 (-2.48, -1.30)*	-1.78 (-2.37, -1.19)*
- at age 85 years	-3.40 (-5.27, -1.54)*	-3.36 (-5.16, -1.56)*
Cadence (steps/min)§		
- at age 65 years	0.18 (-0.43, 0.79)	0.18 (-0.44, 0.80)
- at age 75 years	-0.72 (-1.03,-0.40)*	-0.70 (-1.03, -0.37)*
- at age 85 years	-1.62 (-2.60, -0.63)†	-1.58 (-2.59, -0.58)†
Step length (cm)§		
- at age 65 years	-0.27 (-0.71, 0.17)	-0.17 (-0.56, 0.22)
- at age 75 years	-0.65 (-0.88, -0.43)*	-0.59 (-0.80, -0.38)*
- at age 85 years	-1.04 (-1.76, -0.32)†	-1.02 (-1.66, -0.38)†
Step width (cm)§		
- at age 65 years	-0.05 (-0.23, 0.12)	-0.07 (-0.23, 0.10)
- at age 75 years	0.12 (0.03, 0.21)†	0.13 (0.04, 0.22)†
- at age 85 years	0.30 (0.02, 0.59)‡	0.33 (0.06, 0.60)‡
DSP (%)§		
- at age 65 years	-0.00 (-0.23, 0.23)	0.00 (-0.21, 0.21)
- at age 75 years	0.27 (0.15, 0.39)*	0.32 (0.20, 0.43)*
- at age 85 years	0.54 (0.17, 0.92)‡	0.63 (0.29, 0.97)*

Notes: *$p<0.001$; †$p<0.01$; ‡$p<0.05$;
§ Quadratic term
β=beta–coefficient; CI=confidence interval; DSP=double support phase.

4.5 Discussion

The key findings in this cross-sectional, population-based study are that age was significantly associated with a wide range of gait variables, and that these associations were most pronounced for older women. Older men and women tended to walk more slowly, with smaller steps, larger step widths, and a longer DSP, than their younger counterparts. Older women also walked with a slower cadence.

Decrease in speed [4, 6, 25-29] and step length [25, 28] and an increase in the DSP [28] with advancing age have been found in other population-based studies of older adults and in samples of healthy volunteers [14, 17, 19]. Only in a few [9, 12, 26, 29] previous studies have these associations been found to be more pronounced at older ages. In the only population-based study examining both men and women, these stronger associations were found in both sexes [26], whereas in this study the stronger associations were seen in older women only. The peak speed was estimated for 65-year-old women, consistent with other studies reporting decline in the 7th decade [11, 12, 18, 26]. For men, a linear association was observed between age and speed. Previous studies [14, 18] have found that declines in speed for men commence before the 7th decade, prior to the age of the youngest men in our study.

Previous results have been inconclusive regarding the association between age and cadence, with the majority of studies reporting a decrease [11-13, 25], and one reporting no change with increasing age [21]. In this study, cadence was negatively associated with age in older women, but not in men. Step length and cadence are the determinants of speed. It is possible that, in older women, a decrease in both step length and cadence contributes to the decrease in velocity, whereas men are able to maintain cadence well into older age.

Step width and DSP, key gait variables related to balance and falls risk in older people [11, 34], were positively associated with age in both men and older women in the present study. The few previous studies of older adults show conflicting findings, suggesting that step width decreases [22] or increases with age [28] and that DSP remains unchanged [21] or increases [11, 28]. In this study, stronger associations were seen for older women. It is possible that older women are less able to compensate for poorer balance and therefore require a greater increase in DSP and step width in an attempt to maintain stability. Further research is needed to verify the associations and sex differences between age and step width and DSP found in this study.

The results of this study may have implications for public health, particularly with respect to the stronger associations found between gait variables and age in older women. Decreased speed, cadence, and step length, and increased DSP and step width, are predictive of future falls [5, 6, 21, 34], loss of function, hospitalisation, and increased mortality [7, 35, 36]. Therefore, the accelerated changes in gait for women commencing in their 60's may put them at greater risk. In addition, the average walking speed for women in the 80 to 86 year age group was < 1 m/s, a rate that has been reported to be predictive of major health-related events [36]. Previous studies have suggested that gait speed be used as a quick and easy screening tool, as it can reflect early clinical or subclinical disease in multiple systems [7, 35]. Screening of gait in people, particularly women, older than 65 years may therefore help to identify those persons at high risk and potentially require preventative interventions.

One question is whether gait variables are a more proximal indicator of falls risk, reflecting the insidious effects of chronic diseases such as arthritis [37], declines in muscle strength [21], and other factors that increase the risk of falling and become increasingly more pronounced for older women [19, 38]. If gait parameters are better predictors of risk of falling than the factors underlying them, their ease of measurement would make them worthy candidates as a falls risk screening tool.

In interpreting these findings, it is important to recognise the intercorrelation between the gait variables. We decided to present results for five of these variables for two key reasons. First, knowledge of how these variables are associated with age is important from both biomechanical and clinical perspectives. Understanding which components of gait are age-related can help in formulating treatments to maintain walking speed in older adults. For example, our results suggest that preventive programs for men should focus on maintaining step length rather than cadence to maintain a functional walking speed, whereas in women programs should focus on both step length and cadence. Further research is needed into the mechanisms underlying change in each gait variable and which variables best predict falls and adverse health events. Second, using the method of Cheverud [39], we estimated the number of independent quantities among these five variables. The result was 4.2, suggesting that the information in those five variables would not be captured by any subset of four of them.

The specific causes underlying the observed age-related decline in gait could not be examined in this study. It is possible that age-related neurological or musculoskeletal disease contribute

in part to these changes in gait [40, 41]. Although the presence of self-reported chronic disease in this study was independently associated with some gait variables, its inclusion as a term in the final models did not remove the independent associations between age and the gait variables. The independent associations between age and gait after adjustment for chronic disease suggest that factors other than chronic disease may explain the age-gait associations. Other unmeasured factors such as decline in sensorimotor systems [4], impaired joint range of movement [40], pain [19], reduced physical activity [19], and fear of falling [42] may also contribute to impaired gait with ageing and require further study.

This study adds significantly to knowledge of ageing and gait by providing data on a wide range of quantitative gait measures in a large sample of both men and women. It is also one of very few population-based studies in the field, making these results more generalisable than those from smaller convenience samples reported by the majority of previous studies. However, these findings are limited by their cross-sectional nature, with longitudinal follow-up needed to characterise actual change in gait with ageing. In addition, testing was performed in a flat indoor environment, with further study needed to include more challenging, 'real life' situations such as walking over obstacles and dual tasking.

In summary, all gait variables were associated with age, except for cadence in men. Sex differences in some of these associations suggest that the ageing process may affect gait in men and women differently. Future research needs to consider these important sex differences as a basis for understanding mechanisms underlying changes in gait with advancing age.

4.6 Postscript

The results from this chapter showed that poorer performance on a range of temporal and spatial gait measures – gait speed, cadence, step length, DSP and step width - are associated with advancing age, and that the associations appear to be stronger in older women. The next step is to investigate whether variability in gait is associated with age and, if so, what form the relationships take. This issue will be examined in the next chapter. The importance of that work is that measures of gait variability have shown promise of being more sensitive indicators of falls risk in older people than the gait measures examined in this chapter.

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Appendix 4A has been removed for copyright or proprietary reasons.

Callisaya ML, Au BT, Blizzard L, Schmidt MD, McGinley JL, Velandai KS, Subject-matter considerations in assessing the fit of a linear regression model. Australasian Epidemiologist 2007; 14.2:35-37

Appendix 4B: Subject-matter considerations in assessing the fit of a linear regression model

Background

Gait disorders become increasingly common with age, with the prevalence of abnormal gait reported to be as high as 35% in adults over 70 years [1]. Gait problems are associated with falls and loss of independence, which can lead to hospitalisation, institutionalisation [2] and increased mortality [1]. A better understanding of how gait is affected by ageing may assist in targeting interventions to prevent these public health problems.

To investigate these issues, we conducted a study of gait among the first 223 participants in the Tasmanian Study of Cognition and Gait [3]. This is a population-based study of the neural correlates of gait, balance and cognition in 60-86 year old residents of southern Tasmania. Gait speed was measured using the 4.6 metre *GAITRite* system (CIR Systems Inc. Clifton NJ, USA). The *GAITRite* is a portable carpet walkway with embedded pressure sensors that collects gait data electronically as a participant walks.

Modelling the relationship of gait speed with age

For the 120 men in the sample, there was an inverse linear relationship between gait speed and age. We pay no more attention to them.

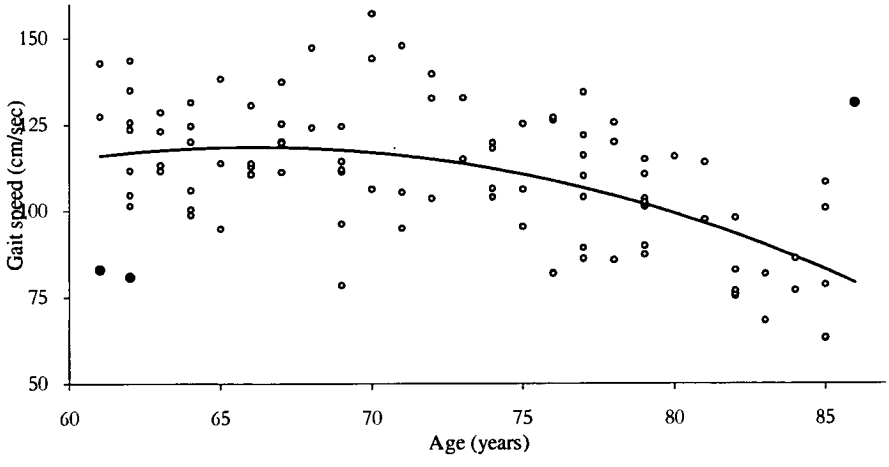

Figure 1: Relationship between gait speed and age in the population sample of 103 women aged 60–86 years

The relationship between gait speed and age for the 103 women in the sample is shown in Figure 1. As for the men, older subjects tended to walk slower, on average, than younger subjects. In the case of the women, however, the relationship was non-linear.

The fitted line is from the linear regression of gait speed (S) on age (Age) and the square of age (Age^2):

$$S_j = \beta_0 + \beta_1 \times Age_j + \beta_2 \times Age_j^2 + \varepsilon_j$$

where β_0, β_1 and β_2 are parameters to be estimated, ε_j denotes the error for each subject, and subscript j indexes subjects ($j = 1, 2, ...n$ where $n = 103$). The errors are assumed to be independent of one another, have zero value on average, have a common variance, and follow a normal distribution.

The result of estimating this linear regression model using Stata 9.0 (StataCorp LP, Texas) was:

Source	SS	df	MS		Number of obs =	103
					F(2, 100) =	19.74
Model	12007.2735	2	6003.63677		Prob > F =	0.0000
Residual	30414.5256	100	304.145256		R-squared =	0.2830
					Adj R-squared =	0.2687
Total	42421.7991	102	415.899991		Root MSE =	17.44

Speed	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Age	13.18022	5.311154	2.48	0.015	2.643037	23.71739
Age2	-.0996957	.0364839	-2.73	0.007	-.1720787	-.0273127
_cons	-317.0258	191.6859	-1.65	0.101	-697.3251	63.27351

The fitted model is:

$$\hat{S}_j = \hat{\beta}_0 + \hat{\beta}_1 \times Age_j + \hat{\beta}_2 \times Age_j^2$$

where $\hat{S}_j$ is the value of gait speed predicted from subject age using estimates $\hat{\beta}_0 = -317.0258$, $\hat{\beta}_1 = 13.18022$ and $\hat{\beta}_2 = -0.0996957$. The contribution of Age^2 to model fit is statistically significant (P=0.007). The inclusion of this covariate increased the explained proportion of total variation in speed from $R^2 = 0.2295$ in a model with Age as the sole covariate (data not shown), to $R^2 = 0.2830$ in this model.

That part of each observation not explained by the model is the observed error or residual:

$$\hat{\varepsilon}_j = S_j - \hat{S}_j$$

where $\hat{\varepsilon}_j$ is an estimate of the unobserved error ε_j for the j^{th} observation. If the fitted model is appropriate for the data, the observed residuals $\hat{\varepsilon}_j$ should exhibit properties consistent with the assumptions made about the ε_j.

An analysis of the observed residuals for these data revealed nothing untoward. Whilst slightly right-skewed (skewness = 0.25), the residuals were almost mesokurtic (kurtosis = –0.14) and satisfied the several tests of homoskedasticity and normality provided in the software package we used. Moreover, no pattern was obvious in a plot of the residuals against the fitted values.

Of more concern was the inverted-U shape of the fitted line. Our cross-sectional sample does not allow inferences on changes in the gait speed of individuals over time as they age, but Figure 1 tempts readers to draw the longitudinal inference that gait speed initially increases and only begins to decline after the midpoint of the 7th decade of life. That seemed implausible to us.

Three data points appeared to be prominent in determining the location and shape of the fitted line. They represented two slower younger women (aged 61 and 62 years) at lower left of the plot, and a speedy 86 year old at upper right. They are marked in Figure 1. To understand their impact, we examined case-wise diagnostics for leverage, consistency and influence.

Leverage in the linear regression model

The general form of the linear regression model with K covariates ($X_1, X_2, ...X_K$) is:

$$Y_j = \beta_0 + \beta_1 X_{j1} + \beta_2 X_{j2} + ... + \beta_K X_{jK} + \varepsilon_j$$

It can be written in matrix form as $\mathbf{y} = \mathbf{X\beta} + \boldsymbol{\varepsilon}$ where:

$$\mathbf{y}=\begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ y_n \end{bmatrix},\ \mathbf{X}=\begin{bmatrix} 1 & X_{11} & X_{12} & . & . & X_{1K} \\ 1 & X_{21} & X_{22} & . & . & X_{2K} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ 1 & X_{n1} & X_{n2} & . & . & X_{nK} \end{bmatrix},\ \boldsymbol{\beta}=\begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ . \\ \beta_K \end{bmatrix},\ \boldsymbol{\varepsilon}=\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ . \\ . \\ \varepsilon_n \end{bmatrix}$$

The ordinary least squares solution for $\boldsymbol{\beta}$ is:

$$\hat{\boldsymbol{\beta}}=(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y}$$

where $\mathbf{X}'$ is the transpose of the $n\times(K+1)$ data matrix $\mathbf{X}$ formed by exchanging its rows and columns, $\mathbf{X}'\mathbf{X}$ is the $(K+1)\times(K+1)$ matrix of sums of products and cross-products, and $(\mathbf{X}'\mathbf{X})^{-1}$ is the inverse of $\mathbf{X}'\mathbf{X}$ with the property that $(\mathbf{X}'\mathbf{X})(\mathbf{X}'\mathbf{X})^{-1}=\mathbf{I}$ where $\mathbf{I}$ is an identity matrix that has ones on the leading diagonal and zeros elsewhere.

The fitted values from the model are:

$$\hat{\mathbf{y}}=\mathbf{X}\hat{\boldsymbol{\beta}}=\mathbf{X}\left[(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y}\right]=\mathbf{H}\mathbf{y}$$

where $\mathbf{H}=\mathbf{X}(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'$ is the $n\times n$ projection matrix that maps $\mathbf{y}$ into $\hat{\mathbf{y}}$ ("**y**hat") and has been dubbed the "hat" matrix. Its diagonal elements are the leverage values. They measure the distance of the values of the covariates from the middle of the data in X-space, and are used to identify unusual covariate values that may unduly influence the parameter estimates.

ID	Speed (cm/sec)	Age (years)
1	121	60
2	114	70
3	104	78
4	84	84
Mean		73

In an attempt to better elucidate the meaning of leverage, consider the hypothetical data on gait speed and age for $n=4$ subjects presented in age order in the table. Suppose that we plan to fit to these data the simple linear regression model:

$$S_j=\beta_0+\beta_1\times Age_j+\varepsilon_j$$

We can write that model in matrix form as $\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}$ where:

$$\mathbf{y} = \begin{bmatrix} 121 \\ 114 \\ 104 \\ 88 \end{bmatrix}, \quad \mathbf{X} = \begin{bmatrix} 1 & 60 \\ 1 & 70 \\ 1 & 78 \\ 1 & 84 \end{bmatrix}, \quad \boldsymbol{\beta} = \begin{bmatrix} \beta_0 \\ \beta_1 \end{bmatrix}, \quad \boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \end{bmatrix}$$

Using matrix algebra, we would find that the 4×4 hat matrix is:

$$\mathbf{H} = \mathbf{X}(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}' = \begin{bmatrix} 0.772 & 0.370 & 0.049 & -.191 \\ 0.370 & 0.278 & 0.204 & 0.148 \\ 0.049 & 0.204 & 0.327 & 0.420 \\ -.191 & 0.148 & 0.420 & 0.623 \end{bmatrix}$$

The leverage values for the four subjects are the diagonal elements $h_{11} = 0.772$, $h_{22} = 0.278$, $h_{33} = 0.327$ and $h_{44} = 0.623$ respectively. The two highest ($h_{11} = 0.772$ and $h_{44} = 0.623$) correspond to the extreme covariate values ($Age = 60$ and $Age = 84$ years respectively). Note that $h_{11} > h_{44}$ because the covariate value corresponding to h_{11} ($Age = 60$ years) lies further from the mean (73 years) than does the covariate value corresponding to h_{44} ($Age = 84$ years).

Applying these understandings to our data, we expected the three prominent observations to have relatively high leverage, and they did. In a regression model with Age and Age^2 as covariates, the speedy 86 year old had the highest leverage ($h = 0.108$), the slow 61 year old had the 7th highest leverage ($h = 0.063$), and the slow 62 year old had the 12th highest leverage ($h = 0.045$).

When fitting a model with $p = K + 1$ parameters to a dataset of n observations, a threshold of $2p/n$ for high leverage has been proposed [4]. Observations with values above this cut-off should be investigated. Fitting a model with $p = 3$ parameters (β_0, β_1 and β_2) to $n = 103$ observations results in a cut-off of $2 \times 3/103 = 0.058$ for high leverage. This was exceeded by two of the prominent observations, and nearly reached by the third.

Consistency in the linear regression model

Any observation with a large residual is not consistent with the model. Large residuals identify observations that are unusual in Y-space. The basic diagnostic statistic is the observed residual:

$$\hat{\varepsilon}_j = y_j - \hat{y}_j$$

It is common to make two adjustments. Firstly, because $\hat{\varepsilon}_j$ is calculated from $\hat{y}_j$ that was estimated using the covariate data for the j^{th} observation, unusual values of y_j may be partly masked. To avoid this, use is made of the jack-knife residual:

$$\hat{\varepsilon}_{(-j)} = y_j - \hat{y}_{(-j)}$$

where $\hat{y}_{(-j)}$ is the value predicted for the j^{th} observation by a model re-estimated after deleting the j^{th} observation. Happily, $\hat{\varepsilon}_{(-j)}$ can be calculated from the observed residual and leverage value for that observation:

$$\hat{\varepsilon}_{(-j)} = \frac{\hat{\varepsilon}_j}{1-h_{jj}}$$

Secondly, the observed residuals cannot be compared sensibly with one another because they do not have constant variance. To overcome this limitation, each $\hat{\varepsilon}_{(-j)}$ is standardised by dividing by its estimated standard error:

$$SE\left(\hat{\varepsilon}_{(-j)}\right) = \frac{s_{(-j)}}{\sqrt{1-h_{jj}}}$$

where $s_{(-j)}$ is the root mean squared error of the regression with the i^{th} observation deleted. This gives the studentised residual:

$$r_j = \frac{\hat{\varepsilon}_j}{s_{(-j)}\sqrt{1-h_{jj}}}$$

A rule-of-thumb is that studentised residuals greater than 2 in absolute value identify observations that should be investigated. This rule is based on the significance of r_j as a *t*-

statistic, and ignores the multiple testing involved. In our data, the speedy 86 year old had the highest absolute studentised residual ($r = 3.32$), the slow 62 year old had the 4th highest ($r = -2.15$), and the slow 61 year old had the 5th highest ($r = -1.98$).

Influence in the linear regression model

Influence measures the effect of deletion of an observation on the parameter estimates $\hat{\boldsymbol{\beta}}$. It assesses $\Delta\hat{\boldsymbol{\beta}} = \left[\hat{\boldsymbol{\beta}} - \hat{\boldsymbol{\beta}}_{(-j)}\right]$ where $\hat{\boldsymbol{\beta}}_{(-j)}$ is the estimate of $\boldsymbol{\beta}$ made after deleting the j^{th} observation.

An overall measure of $\Delta\hat{\boldsymbol{\beta}}$ is Cook's distance:

$$D_j = \frac{1}{K+1} \times \frac{1}{s^2}\left(\hat{\boldsymbol{\beta}} - \hat{\boldsymbol{\beta}}_{(-j)}\right)' \mathbf{X}'\mathbf{X}\left(\hat{\boldsymbol{\beta}} - \hat{\boldsymbol{\beta}}_{(-j)}\right)$$
$$= \frac{1}{K+1} \times r_j^2 \times \frac{h_{jj}}{1-h_{jj}}$$

It combines information on leverage and consistency – the D_j for an observation is high if its leverage $\left(h_{jj}\right)$ or studentised residual $\left(r_j\right)$ is high, or if both are at least moderately high.

Values of Cook's distance greater than $4/n$ should be investigated [5]. In our data, the three largest values were those for the speedy 86 year old ($D = 0.405$), the slow 61 year old ($D = 0.085$), and the slow 62 year old ($D = 0.070$). Each comfortably exceeded the cut-off ($4/103 = 0.039$). Their high influence was due to leverage and inconsistency – each had high leverage and a large studentised residual.

A covariate-specific version of Cook's distance is DFBETA, which is the scaled change in each parameter estimate due to deleting the j^{th} observation:

$$df_{jk} = \frac{\hat{\beta}_k - \hat{\beta}_{k(-j)}}{s_{(-j)}\sqrt{(\mathbf{X}'\mathbf{X})^{-1}_{jj}}}, \quad k = 0,1,2...K$$

where $(\mathbf{X}'\mathbf{X})^{-1}_{jj}$ is the element in row j and column j of $(\mathbf{X}'\mathbf{X})^{-1}$.

DFBETAs in excess of $2/\sqrt{n}$ should be investigated [4]. For our data, this produces a cut-off ($2/\sqrt{103} = 0.197$) that was comfortably exceeded by each of the prominent observations:

- the speedy 86 year old had the highest DFBETA for each of the intercept $\left(df_0 = 0.841\right)$, the *Age* covariate $\left(df_1 = -0.869\right)$ and the Age^2 covariate $\left(df_2 = 0.898\right)$;
- the slow 61 year old had the 2nd highest DFBETA for the each of the intercept $\left(df_0 = -0.383\right)$, the *Age* covariate $\left(df_1 = 0.368\right)$ and the Age^2 covariate $\left(df_2 = -0.355\right)$;
- the slow 62 year old had the 4th highest DFBETA for the intercept $\left(df_0 = -0.306\right)$, and the 5th highest DFBETA for each of the *Age* covariate $\left(df_1 = 0.291\right)$ and the Age^2 covariate $\left(df_2 = -0.278\right)$.

Our strategy for dealing with the outliers

Each of the influential observations was examined. All satisfied the eligibility conditions for inclusion in the study, and none could be excluded on those grounds. No data errors were found, and no contributing factors such as chronic disease were identified. Only one clue came to light: the slow 62 year old was a lady of average height who weighed 116 kgs. Adjusting for height and weight did not resolve the issue, and her Cook's distance actually increased from $DB = 0.070$ to $DB = 0.101$ due to the additional influence she now exerted on the coefficient of the covariate for weight. We adjusted for height and weight in the paper [3], but doing so made no material difference to the outlier analysis and we have not done so here. Similarly a log transformation of gait speed was used in the paper but, to simplify matters, gait speed was not transformed for this analysis.

We eventually decided to exclude the slow 61 year old and the slow 62 year old, but with full disclosure of this in the paper [3]. This produced a more plausible shape in the fitted line for the relationship between gait speed and age, as shown in Figure 2:

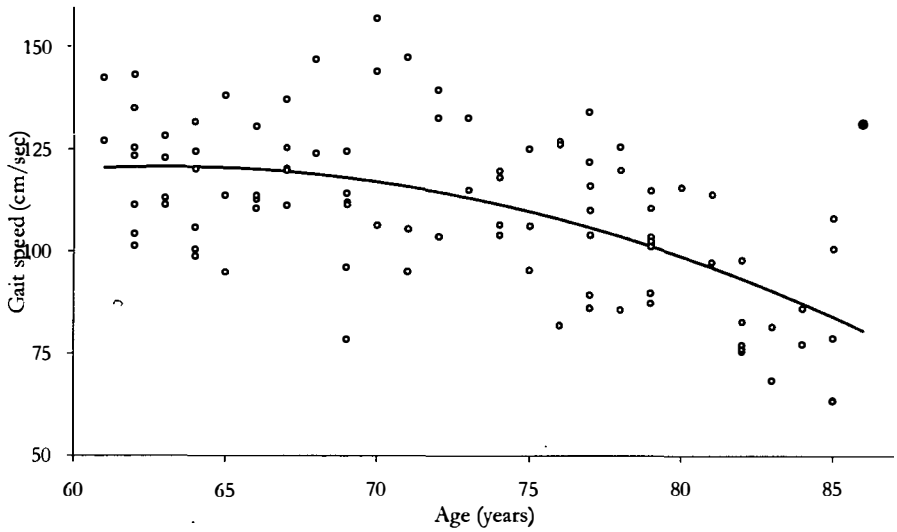

Figure 2: Relationship between gait and age re-estimated after excluding the slow 61 year old and the slow 62 year old

Removing the most influential observation of all – that of the speedy 86 year old – would have increased the downward slope of the fitted line. The change in slope of the fitted line was so minor that we decided to retain this observation, however.

Summary

We have shown how subject-matter considerations can be used in combination with case-wise diagnostics for leverage, consistency and influence to improve a fitted linear regression model.

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Chapter 5: Ageing and gait variability – A population-based study of older people.

5.1 Preface

Results from the previous chapter demonstrated that older people walked with slower gait speeds, shorter steps, longer DSP and wider step widths. In addition older women walked with a slower cadence. The stronger associations between age and gait measures demonstrated by older women may indicate they are at greater risk of mobility decline and associated adverse events such as falls.

More recently there has been increased interest in gait variability measures as complementary and perhaps more sensitive measures of walking function and falls risk. However little is known about how these measures are associated with age or if there are sex differences in these associations that are similar to those in the associations of average measures of gait with age. This chapter will address these issues in a population-based sample of 412 community-dwelling older people. The text of this chapter has been published [1].

5.2 Introduction

The ability to walk efficiently and safely is important for older people to maintain independence and avoid falls [2]. Intra-individual gait variability refers to the fluctuation in the value of a gait measure from one step to the next. It is considered likely to reflect disruptions in intrinsic motor or postural control during walking resulting from age or disease- related decline in the central and peripheral nervous systems [3, 4]. Gait variability measures have been described to be better predictors of falls and decline in mobility than absolute gait measures such as gait speed [5-9]. Given the high risk of falls and mobility problems in older people [10, 11], it is important to clearly characterise the relationship between ageing and gait variability. Such data may enhance the understanding of motor control in older age and assist in defining older people at particular risk of falling.

Although there have been previous studies examining the effect of age on gait variability [8, 12-21], significant gaps still exist in the literature. Firstly, the majority of previous studies have only compared younger with older adults [12-16, 18, 19, 21]. Their results have been inconsistent with some reporting greater gait variability [13, 15, 16, 18, 21] and

others no differences in the younger versus older groups [12, 15, 16, 19, 21] probably reflecting the low subject numbers and different populations sampled. These studies do not provide data on whether age-related changes in gait variability continue in older age. A few small studies of older adults have reported increased variability with advancing age [8, 17, 20] but none have examined both spatial and temporal variables. Furthermore, no data are available on the relationship between age and gait variability at a population level, with prior studies being performed in either convenient samples of healthy volunteers or clinical samples [8, 17, 20]. Age may affect gait speed and other absolute gait measures differently in men and women [22], but it is unknown whether such an interaction between age and sex also occurs with regards to gait variability.

Walking speed slows in older age [13] and there is greater variability in some gait measures at slower speeds [21, 23]. Therefore increased variability found with advancing age may simply be due to slower walking speeds [21] rather than an independent intrinsic phenomenon. Understanding the effect of speed in the relationship between age and gait variability may further clarify mechanisms underlying gait variability.

We conducted a population-based study to investigate the relationship between age and gait variability in older people. The aims were to: (i) study the magnitude and shape of associations between age and a range of gait variability measures; (ii) investigate whether sex modified these associations; and (iii) examine the effect of gait speed on these associations.

5.3 Methods

Study Participants

Participants aged 60-86 years (n=412) were randomly selected from the Southern Tasmanian electoral roll (postcodes 7000-7199) to participate in the Tasmanian Study of Cognition and Gait, conducted at the Menzies Research Institute, Hobart, Tasmania, Australia. Southern Tasmania has a total population of 239,444 people including 46,159 persons aged at least 60 years [24]. Eligible participants were firstly sent an invitation to participate, followed by a phone call. Transport was provided if required. Data collection started in January 2005 and finished in November 2007. Participants were excluded if they lived in a nursing home, were unable to follow simple commands in English, were unable to walk without a gait aid or had any contraindications to magnetic resonance imaging as this was part of a larger study. The Southern Tasmanian Health and Medical Human

Research Ethics Committee approved this study and written consent was obtained from all participants.

Gait Analysis

Gait variables (step time, step length, step width and double support time (DST)) were measured at preferred speed using the 4.6 m *GAITRite* system (CIR Systems, Havertown, PA, USA). Variables are defined in the *GAITRite* manual [25]. Participants started and finished walking two metres before and after the mat to allow for acceleration and deceleration. After two practice trials, participants performed six walks [26]. These variables were chosen as they represent both temporal and spatial measures and have been examined in previous studies of falls risk [5-7]. The variability of each measure was calculated as the standard deviation [4, 7, 8, 18] across all step measures from the six walks.

Other Measurements

Height (cm), weight (kg) and self-reported history of lower limb arthritis, hypertension, stroke, Parkinson's disease, diabetes mellitus, dementia and falls (in the preceding 12 months) were recorded using a standardised questionnaire. To allow estimation of potential non-response bias, non-responders completed a brief phone interview providing similar details about their medical history.

Data Analysis

Differences in demographic, medical and gait characteristics between men and women were analysed using Chi-square test, Student's *t* tests and the two-sample Wilcoxon rank-sum test. Spearman correlation coefficients were used to measure the associations between gait variables, age, height, weight and speed. Linear regression methods were used to assess the relationship between gait measures and age. In multivariable linear regression, the association of gait variables with age independent of height, weight and each chronic disease was assessed. Stroke, dementia and Parkinson's disease were grouped as one variable called central nervous system (CNS) disease due to low subject numbers in each group. Speed was added to determine its effect on the final regression models. At walking speeds other than preferred, temporal and spatial variability are higher, and there is less stability at the head and pelvis [27, 28]. We, therefore, chose a modelling approach including preferred speed as a covariate rather than introducing additional speed walking trials.

In the correlation and regression analysis, gait variables were transformed when required to remove skewness. One slow-paced woman was excluded from analysis after examination for outliers because her data were highly influential in increasing the value of the regression coefficients. This woman was severely physically and cognitively disabled. Statistical interaction between age and sex was assessed by a test of significance of a $(Age \times Sex)$ product term for men, and by a partial-F test for the inclusion of two product terms $(Age \times Sex, Age^2 \times Sex)$ in the model for step time in women.

Finally, log-binomial regression analysis was used to determine whether gait variability measures increased the risk of self-reported falls after adjustment for age, sex, height and weight. For this analysis step time and DST variability were converted to milliseconds. Analyses were performed using Stata 10.0 (StataCorp LP, TX, USA).

5.4 Results

The sample response proportion was 51% (412/804). Non-responders were older (p = 0.01) with a higher incidence of hypertension (p= 0.03). Appendix 5A summarises the characteristics of responders and non-responders. Demographic, medical and gait characteristics are summarised in Table 5.1. An average of 27.3 (SD 5.4) steps was recorded per person. There were no differences between left and right variability measures (p>0.05), and results are based on the average of the left and right sides. Men walked faster (p= 0.01) and had greater variability in step length (p=0.03), DST (p=0.04) and step width (p=0.003) than women. Associations between age, speed and the gait variability measures are shown in Table 5.2. Older age was associated with greater variability in all gait measures in both men and women (p<0.05) and this was demonstrable for increasing age-category as well (Table 5.3). Faster speed was associated with less variability in all measures (p<0.05) except for step width. All relationships were linear, except for a curvilinear association (p<0.001) between age and step time variability for women (Figure 5.1). Results of the multivariable linear regression of age with gait variability measures adjusting for height and weight are shown in Table 5.4. Age remained positively associated with all measures of gait variability in both men and women. In women, the association between age and step time variability was stronger in the older age groups.

There was little change to the associations even after controlling for the presence of each chronic disease. Furthermore, chronic diseases were not associated with any of the gait

variability measures except for self-reported history of arthritis, which was associated with greater step time variability in both sexes ($p<0.01$).

Table 5.1 Sample characteristics (n=411)

Characteristic	Males (n=235)	Females (n=176)
Age, mean (SD)	72.4 (7.0)	71.6 (7.1)
Height [cm], mean (SD)*	172.6 (6.4)	159.5 (6.0)
Weight [kg], mean (SD)*	82.8 (13.9)	71.2 (14.1)
Self- reported Medical History, n(%)		
Hypertension	112 (47.7%)	91 (51.7)
Diabetes	35 (14.9)	16 (9.1)
Stroke	22 (9.4)	12 (6.8)
Parkinson's Disease	2 (0.9)	0 (0.0)
Dementia	2 (0.9)	0 (0.0)
Arthritis	97 (41.3)	85 (48.9)
Falls in previous 12 months	27 (11.5)	42 (23.9)
Gait characteristics, mean (SD)		
Speed [cm/sec]‡	116.03 (21.07)	110.60 (21.11)
Cadence [steps/min]*	107.21 (9.04)	114.60 (10.30)
Step time [sec]*	0.56 (0.05)	0.53 (0.05)
Step length [cm]*	64.72 (8.98)	57.55 (7.88)
Double support time [sec]	0.26 (0.05)	0.25 (0.07)
Step width [cm]*	10.96 (2.89)	8.71 (2.49)
Step time variability [sec]	0.02 (0.01)	0.02 (0.01)
Step length variability [cm]‡	2.81 (0.95)	2.61 (0.86)
Double support time variability [sec]‡	0.02 (0.01)	0.02 (0.01)
Step width variability [cm]†	2.21 (0.75)	1.99 (0.59)

Notes: *$P<0.001$; †$P<0.01$;‡$P<0.05$
SD – standard deviation; cm – centimetres, kg – kilogrammes, sec – seconds;

Table 5.2 Spearman correlations between subject characteristics and gait variables (n=411)

Men → *Women* ↓	Age	Height	Weight	Speed	Step time variability	Step length variability	Step width variability	DST variability
Age	-	-0.31*	-0.37*	-0.41*	0.26*	0.17†	0.15‡	0.25*
Height	*-0.24†*	-	0.43*	0.29*	-0.09	0.02	0.12	-0.02
Weight	*-0.30**	*0.33**	-	0.08	-0.07	0.03	-0.02	0.06
Speed	*-0.34**	*0.21†*	*-0.10*	-	-0.52*	-0.15‡	-0.07	-0.50*
Step time variability	*0.28**	*-0.10*	*0.06*	*-0.70**	-	0.35*	0.17†	0.46*
Step length variability	*0.27**	*0.03*	*0.13*	*-0.31**	*0.48**	-	0.21†	0.33*
Step width variability	*0.18‡*	*-0.01*	*0.02*	*-0.04*	*0.16*	*0.10*	-	0.16‡
DST variability	*0.30**	*-0.13*	*0.05*	*-0.55**	*0.60**	*0.47**	0.17‡	-

*$P<0.001$; †$P<0.01$; ‡$P<0.05$;
DST=Double support time

Table 5.3 Univariable associations between age and gait variability measures (n=411)

Age group (years)	n	Step time variability	Step length variability	Double support time variability	Step width variability
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Men					
60-64	38	0.020 (0.009)	2.68 (0.85)	0.017 (0.005)	2.10 (0.67)
65-69	57	0.020 (0.013)	2.65 (0.62)	0.018 (0.005)	2.16 (0.76)
70-74	47	0.021 (0.011)	2.71 (0.96)	0.019 (0.006)	2.13 (0.64)
75-79	46	0.024 (0.012)	2.97 (1.30)	0.021 (0.010)	2.19 (0.66)
80-86	47	0.025 (0.010)	3.07 (0.93)	0.023 (0.008)	2.46 (0.92)
Trend*		*P*=0.008	*P*=0.01	*P*=0.00	*P*=0.03
Women					
60-64	40	0.020 (0.009)	2.38 (0.82)	0.019 (0.007)	1.86 (0.56)
65-69	45	0.019 (0.008)	2.53 (0.93)	0.020 (0.006)	1.93 (0.51)
70-74	25	0.021 (0.010)	2.47 (0.80)	0.021 (0.008)	2.14 (0.54)
75-79	39	0.023 (0.014)	2.68 (0.59)	0.023 (0.012)	1.94 (0.59)
80-86	27	0.030 (0.014)	3.10 (1.02)	0.027 (0.013)	2.22 (0.73)
Trend*		*P*=0.00	*P*=0.001	*P*=0.00	*P*=0.03

Notes: *The test of trend reported is the result of a *t*-test of the coefficient of a linear term formed taking consecutive integer scores for age groups (60-64 years=1, 65-69 years=2,...80-86 years=5)

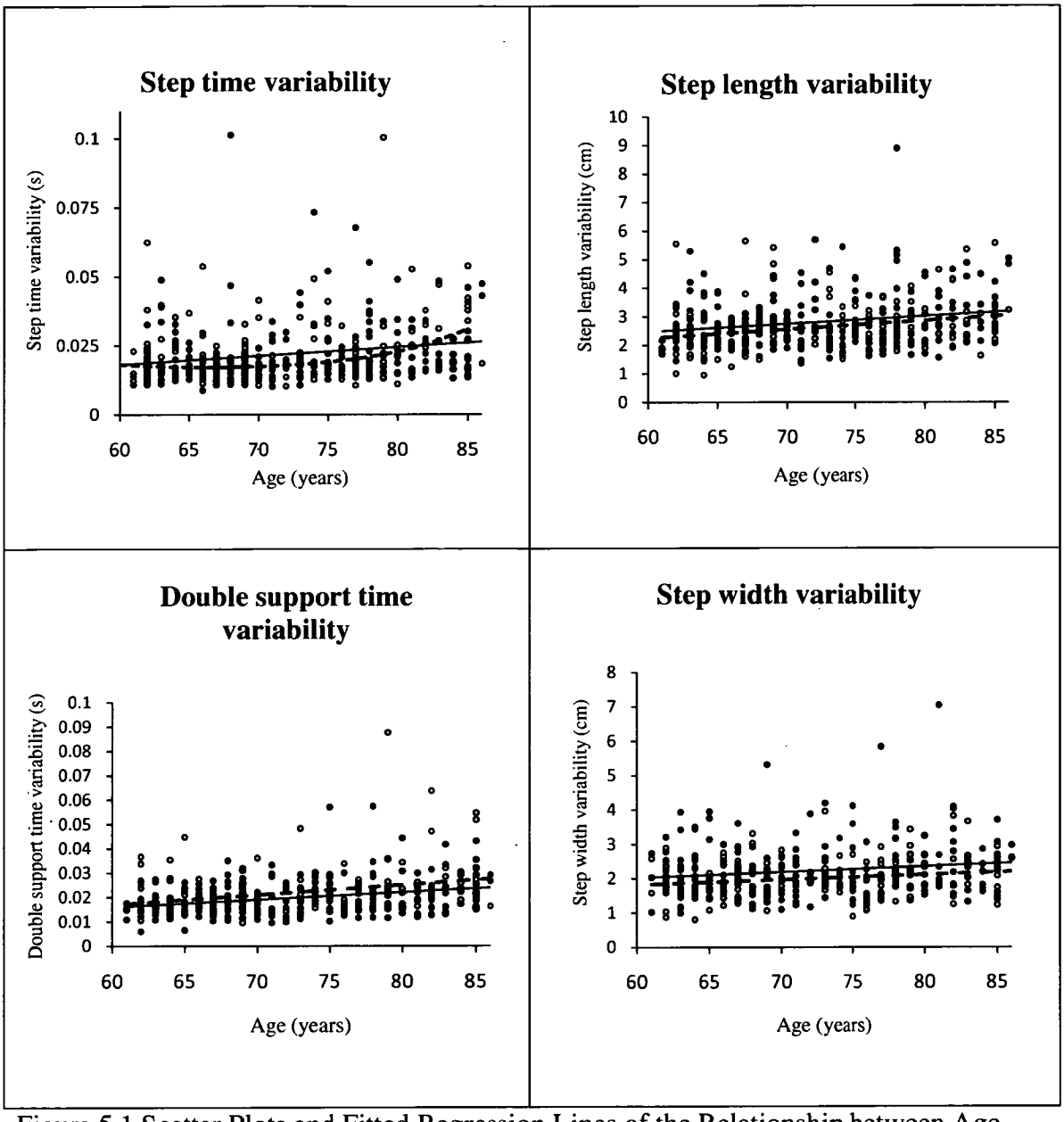

Figure 5.1 Scatter Plots and Fitted Regression Lines of the Relationship between Age and each Gait Measure
● = Men; o = Women; — = Line of best fit for men; --- = Line of best fit for women

Adjusting for speed markedly reduced (range 62-86%) the magnitude of the age coefficient for temporal variability measures, but there was little change in the coefficient of the speed variable in the model with age when compared to its value in the model without age (range 4-10%). In contrast, adjusting for speed reduced the magnitude of the age coefficient by 25% in both sexes for step length variability. For step width variability the magnitude of the age coefficient decreased by 5% in men and increased by 12% in women after adjusting for speed. There were no significant interactions between age and sex for any of the gait variables.

Table 5.4 Multivariable Regression – cross sectional effect of an additional year of age on gait variability measures (n=411)

Gait Measure	Regression coefficients (β) adjusted for: Model 1 β (95% CI)	Model 2 β (95% CI)	Model 3 β (95% CI)
Men			
Step time variability[§]	0.254 (0.133, 0.375)*	0.267 (0.135, 0.400)*	0.064 (-0.063, 0.190)
Step length variability	0.022 (0.008, 0.036)†	0.028 (0.012, 0.043)†	0.021 (0.004, 0.037)†
Step width variability	0.016 (0.004, 0.027)†	0.021 (0.008, 0.033)†	0.020 (0.007, 0.034)†
Double support time variability[§]	0.257 (0.144, 0.371)*	0.314 (0.192, 0.437)*	0.106 (0.091, 0.222)
Women			
Step time variability[§¶]			
- at age 65 years	-0.093 (-0.382, 0.197)	-0.051 (-0.325, 0.222)	-0.084 (-0.334, 0.166)
- at age 75 years	0.455 (0.273, 0.638)*	0.483 (0.295, 0.672)*	0.095 (-0.062, 0.253)
- at age 85 years	2.280 (0.111, 4.449)‡	2.350 (0.139, 4.560)‡	0.329 (-0.285, 0.943)
Step length variability	0.031 (0.015, 0.047)*	0.040 (0.023, 0.057)*	0.030 (0.012, 0.048)†
Step width variability	0.014 (0.002, 0.026)‡	0.017 (0.004, 0.030)†	0.019 (0.005, 0.033)†
Double support time variability[§]	0.297(0.165, 0.429)*	0.316 (0.181, 0.451)*	0.119 (0.089, 0.246)

Notes: *$P<0.001$; †$P<0.01$; ‡$P<0.05$;
Model 1: Unadjusted; Model 2: Adjusted for height and weight; Model 3: Adjusted for height, weight and speed
§ Co-efficient multiplied by 1000; ¶Because of the non-linear association between step time variability and age for women, the cross-sectional effect of an additional year of age was different at each age. Here, we show estimates for 65-, 75- and 85-year-olds.

The risk of a self-reported fall in the past twelve months was increased in those with greater DST variability (Relative risk (RR) 1.03, 95%CI 1.01, 1.05), greater step time variability (RR 1.03, 95% confidence interval (CI) 1.02, 1.04) and greater step length variability (RR 1.19, 95%CI 0.99, 1.43).

5.5 Discussion

This is the first population-based study to characterise in detail the relationships between age and a range of temporal and spatial gait variability measures in older people. We found greater age was associated with greater intra-individual variability in all gait measures, independent of height, weight and self-reported chronic disease. All relationships were linear, except for step time variability in women, which showed stronger associations in older age groups. Previous studies have suggested measures of gait variability are useful indicators of falls [5-8]. Screening of gait in people $\geq$ 60 years may, therefore, be valuable in identifying those at risk.

Adjustment for gait speed produced marked reductions in the estimated effect of age on temporal variability measures, suggesting that speed is an intermediate in the pathway between age and these measures. In contrast, speed is more likely to confound the relation between age and spatial variability measures. This finding has implications for how gait variability measures are analysed in future studies of ageing.

Our findings highlight that variability in step length and step time is greater in older adults in the general population and not just in those with disease [29]. This may represent decline in the automatic stepping mechanism or worsening central motor control [3, 12] and may contribute to an increased risk of falls due to poor foot placement or insufficient postural stability [7]. The greater step time variability with advancing age is consistent with results of other clinical studies of geriatric patients and functionally impaired older adults [8, 20]. However, we found that although there were no significant differences between the sexes, stronger associations between step time variability and age were found in women of older ages. This may indicate that older women may increasingly require closer monitoring of their gait in relation to falls risk and also raises interesting questions about sex-related differences in mechanisms underlying step time variability. To our knowledge, there are no previous studies examining the associations between age and step length variability in older adults. Studies comparing much younger and older adults have been inconsistent, with some studies reporting greater step length variability in older groups [14, 18, 21] and others reporting no difference [12, 15, 16]. These seemingly

conflicting findings may reflect the relatively healthy nature of the older participants or the limited statistical power associated with the small samples. Furthermore, these findings highlight that step length variability and step time variability are greater in older adults in the general population and not just in those with disease [29].

Greater step width and DST variability with advancing age may indicate impaired dynamic balance control during walking [12]. For example, in an attempt to control the centre of mass within their base of support, older people may continually adjust their step width or the duration of DST to compensate for poor balance. Our results are in agreement with a single study of older people finding greater step width variability in older age. Studies comparing step width variability between younger and older adults have found contrasting results, some reporting greater step width variability in older adults [14-16, 18] and others finding no difference by age [12, 21]. Moreover, it is unknown how much step width variability is optimal. There is limited evidence that either excessive or insufficient step width variability may be risk factors for falling [5, 7]. Indeed, Brach et al. hypothesised that a certain minimal level of variability may be needed to adjust step width to maintain stability [5]. Our findings, however, did not reflect this, with only linear relationships found between age and step width variability. Differences in results may be due to different definitions of step width or data collection methods used [5, 7, 21]. For example, data capture with metatarsal markers is likely to systematically vary from that collected with heel markers due to external foot progression [7]. Further work is needed to determine threshold values in each variability measure that are predictive of future risk of falls.

The underlying mechanisms leading to increased variability in each of the gait measures with age are as yet uncertain. It is possible that mechanisms differ across variables [4]. Presence of chronic disease may have contributed to the associations between age and the gait variability measures. For example, diabetes may lead to peripheral neuropathy, possibly reducing stability whilst walking and resulting in greater gait variability [30]. However, the inclusion of self-reported chronic disease in the final models did not significantly alter the associations. This suggests other factors or diseases may explain the associations with age. The importance of the CNS in controlling rhythmical gait is reflected by the increased gait variability found in age-related changes or diseases of the CNS [29] and under dual task conditions [31]. Ageing is associated with changes in brain structure, involving regions that are important for intrinsic automaticity of gait such as the basal ganglia [29], potentially leading to greater gait variability. Psychological factors or

age-related changes in strength and balance have also been found to be associated with an inconsistent walking pattern [4, 8, 20, 32]. In this study, arthritis was the only chronic disease associated with gait, and only with greater step time variability. This may have been due to impairments commonly associated with arthritis such as pain or decreased strength [33] interfering with timing of steps. The lack of association between other chronic diseases and gait variability in this study could have been due to low numbers, mildness of disease or the relatively unchallenging task.

To our knowledge, no previous studies have examined the effect of speed on the relationship between age and gait variability in the general older population. Our results suggest that speed is an intermediate in the pathway between age and temporal gait variables, indicating that age-related changes in temporal variability measures may be largely due to reduced walking speed. It is possible, that at slower walking speeds, the temporal automaticity of gait is impaired, resulting in reduced consistency from step to step. Spatial variability measures were less dependent on gait speed, and speed did not appear to mediate the relationship of spatial variability with age. These results suggest gait speed should be considered particularly when measuring temporal variability measures in further research and clinical practice.

The strengths of this study are its population-based design, the size of the sample, the use of sophisticated measurements by trained staff using standardised protocols and the range of measures of gait variability studied. The association of gait variability measures with retrospective recall of self-reported falls in our sample was consistent with previous reports [19], supporting the validity of the gait measures. The random selection of participants from a defined population enhances the generalisability of the findings to older people in general. In addition, we examined the effect of speed on these relationships and tested for non-linear associations and interactions, adding significantly to knowledge in the field. Our findings are, however, limited by their cross-sectional nature, with longitudinal follow-up needed to characterise actual changes in gait variability with ageing. In addition, we sampled a relatively small number of steps using a computerised mat. This restricted us to collecting the magnitude of variability rather than examining the long-range correlations in these step fluctuations [3, 34]. However, it did allow us to collect both spatial and temporal variables, and participants were unlikely to be affected by fatigue over the short distance walked. Such simple measurement protocols have particular potential for inclusion in clinic-based screening.

Key points

- In this first population-based study of older adults we found that older age was associated with greater temporal and spatial variability in both sexes.
- Step time variability was greater in women of older age.
- Gait speed should be considered particularly when measuring temporal variability measures in further research and clinical practice.
- Further research is needed to study optimal levels and determinants of each gait variability measure, and the role of gait variability as a component of falls risk screening programmes

5.6 Postscript

Older age was associated with greater variability in all gait measures. In contrast to the average measures of gait, for older women stronger associations were only found for step time variability. If programs to prevent greater gait variability in older age are to be implemented a better understanding of the underlying mechanisms are required. Age explained only a small proportion of the variance of each of the gait variability measures in this study. Performance on sensorimotor factors may better explain gait variability because impaired performance in these measures may represent age-related deterioration, early pathology and clinical disease. This is the topic of chapter 7, in which the associations of gait variability with sensorimotor function deficit is examined. To lead that work, an investigation is undertaken in the next chapter (Chapter 6) of whether poorer performance in sensorimotor function contributes to poorer gait patterns in respect of average measures of gait that are found in older age.

Gait speed appeared to be an intermediate in the relationship between age and temporal gait variability measures. These results suggest that, in future studies, it may be necessary to control for gait speed either in the design or in the analysis.

5.7 References

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Appendix 5A: Characteristics of responders and non-responders

Characteristics of responders (n=412) and non-responders (n=223)		
	Responders	Non-responders
Age band, n (%)		
60-64	78 (18.9)	31 (13.9)
65-69	102 (24.8)	36 (16.1)
70-74	72 (17.5)	42 (18.8)
75-79	85 (20.6)	70 (31.4)
80-86	75 (18.2)	44 (19.7)
Sex, n (%)	177 (43.0)	110 (49.4)
Past falls 12 months, n (%)	69 (16.8)	41 (18.4)
Hypertension, n (%)	203 (49.3)	130 (58.3)
Diabetes, n (%)	51 (12.4)	34 (15.3)
Stroke, n (%)	34 (8.3)	21 (9.4)

Chapter 6: A population-based study of sensorimotor factors affecting gait in older people

6.1 Preface

The results from chapter 4 revealed that poorer performance in a number of temporal and spatial gait measures was associated with older age, and that these associations were strongest in older women. To investigate possible factors that may explain why older adults walk with a slower gait speed and cadence, shorter steps, a longer double support phase and a wider step width, we conducted a population-based study of 278 older people, examining the associations between sensorimotor factors and these gait measures. The results are reported in this chapter. The findings are presented separately for men and women because the results from chapter 4 indicated that the associations between age and some gait measures differed between the sexes. A better understanding of these associations may lead to specific targets for intervention programs aimed at avoiding age related gait changes.

This text of this chapter has been published [1]. Additional unpublished analyses are reported in Appendices 6A and 6B. Appendix 6A presents the results of an investigation of the pathways that lead to reduced gait speed. Appendix 6B investigates whether poorer performance in sensorimotor function contributed to the accelerated slowing of gait speed for older women found in chapter 4.

6.2 Introduction

Approximately 30% of older adults have a gait disorder that is associated with loss of independence, falls, hospitalisation, institutionalisation and mortality [2-4]. Age may affect several characteristics of gait including speed (and its contributors, stride length and cadence), step width and double support phase (DSP) [5]. These effects of age on gait may be partly due to deterioration in sensory and motor systems that are important for safe walking. For example, muscle strength, reaction time, balance, sensation and vision have been shown to decline with age [6] or as a consequence of clinical and sub clinical disease [7]. Decline in such sensorimotor abilities are individually associated with slower gait speed and cadence, shorter steps, longer DSP and wider step width in older people [2, 8-11].

Age-related gait decline is more likely to be due to a number of sensorimotor factors, rather than one single factor [12]. Few population-based studies have comprehensively examined the relationships between multiple sensorimotor factors and gait [2, 8, 13, 14]. Furthermore, these studies have tended to examine only one variable such as gait speed [8, 13] or step length [14], included only women [2], and have failed to explore potential interactions involved in these relationships. Examining interactions between such factors may add to knowledge about mechanisms by which older adults maintain mobility. A good understanding of these relationships may inform the development of specific interventions to prevent age-related decline in gait speed (due to shorter steps, increased DSP and /or slower cadence) or wide based gait. Such data would also provide clinicians with an evidence base for community-based programs designed to maintain mobility.

The aim of this population-based study was to examine the relative contributions of multiple sensorimotor factors to a range of gait variables. Specifically we hypothesised that better performance on sensorimotor tests would be associated with faster gait speed and cadence, greater step length, shorter DSP and a smaller step width. Given our previous findings of sex differences in age-related changes in gait [5], we examined this hypothesis separately in men and women.

6.3 Methods

Study Participants

Individuals aged 60 to 86 years (n=278) living in southern Tasmania were randomly selected from the electoral roll to participate in the Tasmanian Study of Cognition and Gait (TASCOG). Southern Tasmania has a total population of 239,444 people including 46,159 persons aged at least 60 years [15]. Individuals were excluded if they lived in a nursing home or were unable to walk without a gait aid. The Southern Tasmanian Health and Medical Human Research Ethics Committee approved this study and written consent was obtained from all participants.

Gait Measures

Gait was measured using a 4.6 metre *GAITRite* walkway (CIR Systems Inc. Clifton NJ, USA). Speed, cadence, step length, step width, and DSP were recorded at preferred speed. Participants started and finished walking two metres before and after the mat to ensure constant walking speed across the mat [16]. After two practice trials, participants performed six walks and gait measures were averaged over the six walks. The *GAITRite*

has been validated against a gold standard three-dimensional motion analysis system [17], and has excellent test-retest reliability in older adults [18].

Sensorimotor Factors

Sensorimotor function was assessed using the short form of the Physiological Profile Assessment (PPA). The PPA is a validated battery of the following sensorimotor measurements used to identify those at risk of falling [19]: (1) Visual contrast sensitivity (VCS) (dB) using the Melbourne Edge Test; (2) Proprioception (cm) using a lower-limb matching task, with an inscribed vertical protractor placed between the seated participant's legs; (3) Maximal isometric quadriceps strength (kg) measured in sitting using a spring gauge; (4) Simple reaction time (ms) using a light stimulus and a finger-press of a switch as the response; (5) Postural sway (mm) using a sway-meter to measure body displacement at the waist level as the participants stand on a foam rubber mat for 30 seconds under two conditions - eyes open and closed. Maximal medial-lateral and anterior-posterior sway (mm) were summed to calculate the final score for each condition. Better performance is indicated by larger scores of VCS and quadriceps strength and lower scores of proprioception, reaction time and sway.

Other Measurements

Height (cm), weight (kg) and self-reported history of lower limb arthritis, stroke, Parkinson's disease, dementia, hypertension, angina, ischemic heart disease, diabetes mellitus and falls (in the preceding 12 months) were recorded using a standardised questionnaire. Non-responders completed a brief phone interview providing their medical history and history of falls in the previous 12 months to estimate potential non-response bias.

Data Analysis

Chi-square and Student *t*-tests were used to compare gait and sensorimotor variables between men and women. In correlation and regression analyses, DSP was log transformed. Partial correlations were first used to estimate the relationships between the sensorimotor and gait variables adjusting for age. Multivariable regression was used to model the effect of each sensorimotor factor on individual gait variables adjusting for age, height and weight. Other sensorimotor factors were also included in models if their association with the gait measure was statistically significant ($p<0.05$) or if their inclusion changed the coefficient estimates of the other covariates by more than ten percent. Statistical interaction between covariates was assessed by including the product of those

covariates in the regression. We carefully checked the scale of the covariates and investigated the model fit particularly in respect to the interaction terms. Analyses were conducted using STATA version 9.0 (StataCorp, Texas USA).

6.4 Results

The sample response proportion was 53% (278/428). People who did not participate (non-responders) were older ($p<0.001$) but did not differ from participants with respect to sex ($p=0.17$), history of hypertension ($p=0.36$), diabetes mellitus ($p=0.46$), stroke ($p=0.53$), ischemic heart disease ($p=0.61$) and previous falls ($p=0.89$). Compared with women, men were taller ($p<0.001$), heavier ($p<0.001$), walked faster ($p=0.04$), had a larger step length ($p<0.001$) and step width ($p<0.001$) but a slower cadence ($p<0.001$). Men had stronger quadriceps strength than women ($p<0.001$), but poorer proprioception ($p=0.02$) (Table 6.1).

Adjusting for age, reaction time and quadriceps strength were the factors most strongly associated with gait speed in both men and women (Table 6.2). For both sexes, quicker reaction time was associated with longer steps, faster cadence and speed, and a shorter DSP. Stronger quadriceps strength was associated with longer steps and faster speed in both sexes and faster cadence in men. Smaller sway (eyes open or closed) was associated with faster speed and longer steps in both sexes, and shorter DSP and smaller step width in women. VCS and proprioception were not associated with any of the gait variables independently of age.

In final multivariable models (Table 6.3), reaction time was an independent predictor of speed and its determinants cadence and step length. The effect of quadriceps strength on step length and speed was modified by body weight in men (p for interaction $=0.01$) and VCS in women (p for interaction $=0.02$), with stronger associations seen in men with lower body weight and women with better VCS. Quadriceps strength predicted cadence independently of other factors in men, but was a confounder in the relationship between reaction time and cadence in women. Postural sway (eyes open) independently predicted step length and speed, but only in men. An interaction was found between VCS and proprioception (p for interaction = 0.02) in predicting speed in women, with weaker associations between proprioception and speed seen in women with better vision.

Table 6.1 Characteristics of the sample (n = 278)

Characteristic	Men (n=154)	Women (n=124)
Age, mean (*SD*)	72.7 (6.8)	72.1 (7.2)
Height in cm, mean (*SD*)*	172.6 (6.4)	159.2 (5.2)
Weight in kg, mean (*SD*)*	82.8 (14.5)	70.9 (14.1)
Medical History (self reported), n (%)		
Hypertension	65 (42.2)	61 (49.2)
Angina	31 (20.1)	15 (12.1)
Ischemic heart disease †	30 (19.5)	10 (8.1)
Diabetes	19 (12.3)	13 (10.5)
Stroke	11 (7.1)	10 (8.1)
Parkinson's disease	1 (0.7)	0 (0.0)
Dementia	2 (1.3)	0 (0.0)
Lower limb Arthritis	67 (43.5)	59 (48.4)
Lower limb Pain	52 (36.4)	52 (46.0)
History of falls in the past 12 months †	19 (12.3)	31 (25.0)
Gait Variables, mean (SD)		
Speed, cm/sec‡	115.17 (20.43)	110.21 (19.22)
Cadence, step/min*	107.04 (8.66)	115.05 (9.94)
Step Length, cm*	64.37 (8.83)	57.26 (7.16)
Step width, cm*	10.89 (3.01)	8.65 (2.56)
Double support phase, %	23.45 (3.35)	24.25 (3.82)
Sensorimotor Variables, mean (SD)		
Visual contrast sensitivity, dB	20.4 (2.1)	20.8 (2.4)
Reaction time, ms	227 (46)	236 (39)
Proprioception, degrees‡	1.6 (1.3)	1.3 (1.1)
Quadriceps strength, kg*	35.8 (12.5)	25.5 (8.8)
Sway eyes open, mm	23 (17)	21 (8)
Sway eyes closed, mm	43 (33)	48 (47)

Notes: *$P<0.001$; †$P<0.01$; ‡$P<0.05$;
SD - standard deviation; dB - decibel, cm – centimetre, mm – millimetres, ms – milliseconds, kg - kilograms;

Table 6.2 Age-adjusted partial correlations between sensorimotor and gait variables

Women	Speed (cm/sec)	Cadence (steps/min)	Step Length (cm)	Step width (cm)	DSP (%)
VCS	0.15	0.11	0.13	-0.05	-0.09
Reaction time	-0.23‡	-0.21‡	-0.19‡	0.12	0.19‡
Proprioception	-0.13	-0.09	-0.10	0.08	0.06
Quadriceps strength	0.30†	0.14	0.32*	0.05	-0.16
Sway eyes open	-0.20‡	-0.17	-0.15	0.13	0.19‡
Sway eyes closed	-0.20‡	-0.13	-0.19‡	0.25†	0.13
Men					
VCS	0.05	0.04	0.05	-0.09	-0.13
Reaction time	-0.30*	-0.18‡	-0.29*	0.10	0.26†
Proprioception	-0.13	-0.04	-0.16	-0.00	0.02
Quadriceps strength	0.25†	0.19‡	0.22†	-0.07	-0.04
Sway eyes open	-0.19‡	-0.05	-0.23†	0.06	0.15
Sway eyes closed	-0.12	-0.06	-0.11	-0.04	0.03

Notes: *P<0.001.†P<0.01.‡P<0.05
DSP, double support phase; %, percentage; VCS, visual contrast sensitivity

Postural sway (in both sexes) and quadriceps strength (in women only) were independent predictors of DSP. In men, the effect of reaction time in predicting DSP was modified by height (p for interaction = 0.004) and quadriceps strength (p for interaction = 0.04) such that stronger associations were found in taller men with poorer strength. In women, the effect of postural sway (eyes closed) on DSP was modified by proprioception (p for interaction = 0.06) with a stronger association seen for women with poorer proprioception. Postural sway eyes closed was the sole predictor of step width and only in women. The footnotes in Table 6.3 provide information on the critical values of height, weight and the sensorimotor variables that are effect modifiers in the interaction effects.

The strength of the associations between sensorimotor measures and each gait variable are summarised in Table 6.4 as partial R^2 values from the final multivariable models

6.5 Discussion

In this sample from the general older population, several important and modifiable sensorimotor factors were associated with gait speed, its determinants (step length and cadence) and DSP, but only postural sway was associated with step width. Among the sensorimotor factors, quadriceps strength and reaction time explained the greatest proportion of variance. The pattern of these associations varied between the sexes.

Quadriceps strength explained the greatest proportion of variance of gait speed, with greater strength predicting faster speeds for all but the heaviest men (>93kg) and the women with poorest vision (<17dB) (using the results provided in Table 6.3). Other significant covariates of faster speed were quicker reaction time in both men and women, smaller postural sway for men, and better proprioception in all women except those with better vision. These results are generally in agreement with those from the few previous population-based studies showing that multiple sensorimotor factors are associated with speed, with muscle strength being of particular importance [2, 8, 13]. Our study extends previous findings [2, 8, 13] by reporting on both men and women and carefully examining for interaction effects.

Table 6.3 Multivariable associations between sensorimotor and gait variables

Gait measure		Men		Women	
	Predictor variable	Age, Height and Weight Adjusted β (95 % CI)	p value	Age, Height and Weight Adjusted β (95 % CI)	p value
Speed	QS	1.87 (0.58,3.15)	0.005	-2.17 (-4.81, 0.48)	0.11
	Reaction time	-0.10 (-0.16,-0.04)	0.001	-0.09 (-0.16, -0.01)	0.03
	Sway eyes open	-0.16 (-0.31,-0.01)	0.03		
	Proprioception			-27.22 (-49.42,-5.01)	0.02
	VCS			-3.80 (-7.40,-0.20)	0.04
	Weight	0.24 (-0.29,0.77)	0.38		
	QS x weight*	-0.02 (-0.03,-0.00)	0.02		
	VCS x Proprioception†			1.24 (0.17, 2.30)	0.02
	VCS x QS‡			0.13 (0.00, 0.26)	0.04
	R^2	0.39		0.40	
Cadence	QS	0.13 (0.01, 0.24)	0.04	0.13 (-0.09, 0.36)	0.24
	Reaction time	-0.03 (-0.06,-0.00)	0.04	-0.05 (-0.09, 0.00)	0.04
	R^2	0.11		0.12	
Step Length	QS	0.80 (0.30, 1.31)	0.002	-0.92 (-1.84, 0.00)	0.05
	Reaction time	-0.04 (-0.06,-0.02)	0.001	-0.03 (-0.06, -0.01)	0.02
	Sway eyes open	-0.09 (-0.15,-0.03)	0.003		
	VCS			-1.13 (-2.24, -0.01)	0.05
	Weight	0.06 (-0.15,0.27)	0.58		
	QS x weight§	-0.01 (-0.01,-0.00)	0.01		
	QS x VCS¶			0.06 (0.01, 0.10)	0.02
	R^2	0.49		0.45	
DSP	QS	9.65 (-0.21, 19.52)	0.06	-3.77 (-6.68,-0.85)	0.01
	Reaction time	-15.93 (-27.41,-4.44)	0.007		
	Sway eyes open	1.21 (0.18, 2.26)	0.02	3.23 (0.33, 6.21)	0.03
	Sway eyes closed			-0.16 (-0.98,0.67)	0.71

	Proprioception			-30.90 (-61.32, -0.48)	0.05
	Height	-26.54 (-43.15,-9.94)	0.002		
	Reaction time x height#	0.11 (0.03, 0.18)	0.004		
	Reaction time x QS**	-0.05 (-0.09, -0.03)	0.04		
	Proprioception x sway eyes closed††			0.29 (-0.02, 0.60)	0.06
	R^2	0.36		0.38	
Step width	Sway eyes closed			0.02 (0.01, 0.03)	0.001
	R^2	0.13		0.18	

Notes: β, beta–coefficient; CI, confidence interval; DSP, Double Support Phase; All DSP coefficients are multiplied by 100; VCS, visual contrast sensitivity

* Faster speed is associated with greater quadriceps strength (QS) in men, but the association is progressively reduced by increasing weight and disappears at weights > 93kg.

† Faster speed is associated with better proprioception in women, but the association is progressively reduced by better VCS and disappears at levels of VCS >21dB

‡ Faster speed is associated with increased QS in women, but the association is progressively reduced by poorer VCS and disappears at levels of VCS <17dB

§ Longer step length is associated with increased QS in men, but the association is progressively reduced by increasing weight and disappears a weights>80kg

¶ Longer step length is associated with increased QS in women, but the association is progressively reduced by poorer VCS and disappears at levels of VCS <15dB

Shorter DSP is associated with faster reaction time in men, but is progressively reduced by increasing height and disappears completely at heights > 161cm for men with average QS.

** Shorter DSP is associated with increased QS in men, but is progressively reduced by faster reaction time and disappears completely at values of reaction time < 194ms

†† Shorter DSP is associated with better proprioception in women, but the association is progressively reduced by better sway eyes closed and disappears completely at values of sway eyes closed<107mm

Table 6.4 Partial R^2 values for the regression of gait variables on sensorimotor variables

	Better Visual contrast sensitivity	Quicker reaction time	Better proprioception	Stronger QS	Smaller sway (eyes open)	Smaller sway (eyes closed)
Men						
Faster speed		.05		.07	.02	
Faster cadence		.03		.03		
Longer step length		.04		.06	.03	
Reduced DSP		.09		.03	.02	
Narrower step width						
Women						
Faster speed	.05	.03	.04	.07		
Faster cadence		.03				
Longer step length	.03	.03		.08		
Reduced DSP			.03	.04	.03	.03
Narrower step width						.08

Notes: QS=quadriceps strength; DSP=double support phase

To illustrate and further explore these interactions we calculated the gain in quadriceps strength required to increase speed by 5 cm/sec (using the results provided in Table 6.3), a value described as the smallest clinically meaningful change [20]. For example, a woman with a VCS of 21 (50th percentile) would need an estimated 9 kg increase in strength to increase speed by 5 cm/sec, whereas a woman with a VCS of 23 (75th percentile) would only require an estimated 6 kg increase in strength. A man weighing 80kg (50th percentile) would need an estimated 18kg increase in quadriceps strength to increase speed by 5cm/sec, whereas a man weighing 92 kg (75th percentile) would require an impractical 167 kg gain in strength. Interventions designed to improve mobility may therefore be more effective if multifactorial. For example, interventions to increase speed ideally would involve a weight loss program in men and visual education strategies in women to complement muscle strengthening.

Clinicians routinely examine whether slower speed is the result of shorter steps, a slower cadence or a combination of both. We therefore examined the associations between sensorimotor variables and each of these gait variables. Faster cadence contributed to faster gait speed through its associations with quicker reaction time (in both sexes), and stronger quadriceps strength (in men only). Reaction time and quadriceps strength equally explained the greatest proportion of variance for cadence in men.

Quadriceps strength explained the greatest proportion of variance for step length with greater strength predicting longer steps for all but heavier men and women with the poorest vision. Such interactions were not observed in previous studies in which strength and vision were found to be independent predictors of step length in women [2, 9]. Quicker reaction time in both sexes and smaller postural sway (in men only) also were independent predictors of longer steps. This information may be useful clinically. For example in a community program designed to improve walking speed, older adults with both reduced cadence and step length may benefit from a program designed to improve reaction time and muscle strength. In addition those with reduced step length may also benefit from a balance and weight loss program (in men) or a visual education program (in women).

The associations between sensorimotor factors and DSP [9] or step width [10] have been explored in very few studies and only in convenience samples. These gait variables have been associated with falls in older people [21, 22] and may be measures of dynamic balance during gait [23]. Consistent with this concept we found that smaller postural sway, also a measure of standing balance control, was associated with reduced DSP (in both

sexes) and narrower step width (in women only). However, the variables explaining the greatest variance were stronger quadriceps strength for women and reaction time for men. Postural sway (in women only) was the sole sensorimotor predictor of step width, and this finding is consistent with that of the only previous study examining associations between balance and step width in women [10].

The mechanisms by which each sensorimotor factor affects gait may be different. Poorer quadriceps strength may reduce the propulsive forces and stability required to maintain sufficient cadence, step length and DSP. Slower reaction time may reflect reduced central processing speed due to age-related changes in the brain, and its association with reduced speed may reflect the direct effects of the declining central cognitive control of gait. Alternatively, people with slow reaction times may reduce their cadence and step length and increase DSP (men) as a strategy to compensate for unexpected perturbations and obstacles. The association between sway and DSP may simply reflect the fact that they measure the same construct, with the former indicating static balance and the latter more dynamic balance during gait. However, it is also possible that older people may widen or shorten their steps, and increase their DSP to improve stability and compensate for poor balance.

Some sex differences were observed in the associations between sensorimotor factors and gait variables, possibly reflecting a reliance on different physiological systems. It is also possible that men and women compensate for impairment in physiological systems differently. For example, poor balance (sway) may lead women to increase step width, men to shorten step length and both to increase DSP to improve stability when walking. Alternatively hormonal differences may also play a role. For example, menopause can lead to a rapid decline in muscle strength [24], leaving women to rely more heavily on other factors such as vision. Further research is needed to confirm the sex differences found in this study.

Although a wide range of sensorimotor factors were studied, the models explained only up to 49% of the variance in gait. Other factors such as loss of range of movement, vestibular function, cognition, pain, fear of falling, depression or other sensorimotor factors are likely to also contribute to impaired gait. Further research is needed particularly into the factors contributing to step width considering its association with falling in older adults [22].

Other limitations of this study need to be considered. Firstly, it was cross sectional in nature. The true causal nature of these associations needs to be further explored and

determined in alternate study methodology or in longitudinal analyses. Secondly, whilst the sample response proportion (53%) was much higher than in previous population-based studies [8, 13], the possibility of non-participation bias cannot be discounted.

This study adds significantly to knowledge of the sensorimotor factors associated with walking ability by providing data on a range of quantitative gait measures in a large population-based sample. In addition to providing novel data for men, this study extends previous work by exploring interaction effects between the sensorimotor variables. Furthermore interventions are available to improve strength, balance, reaction time [25] and vision [26]. Therefore these results provide clinicians with potential factors for a more focussed assessment or intervention in those with specific temporal or spatial gait changes.

Key points

- This population-based study provides new insights into the relative contributions of key sensorimotor factors associated with a wide range of gait variables.
- Sensorimotor factors contributed up to 49% of the variance of gait variables.
- Quadriceps strength in both sexes and reaction time in men were the strongest predictors of speed-related gait variables. Postural sway was the only predictor of step width in women only.
- Men and women may rely on different sensorimotor variables to maintain walking.
- The results may assist in designing effective prevention and intervention strategies towards maintaining or improving walking in older people.

6.6 Postscript

A number of sensorimotor factors that are associated with poorer gait patterns in community-dwelling older people were identified in this chapter. These sensorimotor factors were found to be associated with gait independently of age. But, they did not fully explain the associations of age with gait, and did not explain the stronger associations between age and gait speed reported among older women in Chapter 4. The results reported in Appendix 6A suggest a pathway by which the gait and sensorimotor measures in this study contribute to slower gait speed. These potentially modifiable sensorimotor factors could be targeted in programs to prevent age-related walking decline.

Apart from the obvious benefits of preserving independence, it is also possible that maintaining gait speed and performance in other measures of gait in older age may reduce the risk of falling. The question of whether poorer performance in gait measures increases the risk of falling will be the subject of chapter 8.

Having investigated the associations of average measures of gait with sensorimotor function in this chapter, the next chapter (Chapter 7) will report on an investigation of whether sensorimotor factors contribute to gait variability.

6.7 References

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Appendix 6A: The pathways that cumulate in gait speed

Step length and cadence are the components of gait speed. For example step length multiplied by cadence is equal to gait speed. However it is less certain where double support phase and step width occur in this pathway. An additional investigation of the possible pathways that culminate in gait speed is presented in this appendix.

Regression analysis was used to determine the associations between gait measures. Step length and cadence were the dependent variables and DSP and step width the independent variables. Regression coefficients of each independent variable were carefully examined. A gait variable was considered an antecedent in the pathway if its regression coefficient decreased markedly, with minimal change in the regression coefficient of the other gait variable. If the coefficient of each gait variable decreased markedly, this suggested it was a confounder. A marked change was considered to have occurred if the regression coefficient changed by more than 10 percent [1].

Step length and cadence explained 99% (men) and 100% (women) of the model for gait speed. For men, step width ($p = 0.001$) and DSP ($p<0.001$) were both significantly associated with step length in univariable models. When both step width and DSP were added to the step length model, only DSP ($p<0.001$) was an independent predictor. When adjusting the estimated effect on step width for DSP, the regression coefficient for step width decreased by 68% with only a 5% change in the coefficient of DSP suggesting that step width was an antecedent to DSP. For women, the results were similar, but step width ($p=0.01$) remained a significant predictor of step length in the model with DSP ($p<0.001$). When adjusting for DSP the regression coefficient for step width decreased by 49% with only a 9% change in the coefficient of DSP.

For men, DSP was significantly associated with cadence ($p<0.001$), but step width was not ($p=0.23$). When adjusting for DSP, the regression coefficient for step width decreased by 91% with only a 0.9% change in the coefficient of DSP suggesting that step width was an antecedent to DSP on the pathway to cadence. Similar results were found for women. When adjusting for DSP, the regression coefficient for step width decreased by 93% with only a 0.8% change in the coefficient of DSP.

The significant predictors of each gait measure are presented in Table 1.

Table 1. Pathway modelling for the gait variables

Gait variable	Independent variables	Males (n=154)		Females (n=124)	
		β	(95 % CI)	β	(95 % CI)
Gait speed (cm/sec)	Step length	1.76	(1.73,1.79)*	1.93	(1.90, 1.96)*
	Cadence	1.07	(1.04, 1.10)*	0.92	(0.89, 0.94)*
	R^2		0.99		1.00
Cadence (step/min)	DSP	-19.09	(-28.59, -9.60)*	-29.02	(-39.27,-18.78)*
	R^2		0.09		0.21
Step Length (cm)	DSP	-37.45	(-45.66,-29.23)*	-28.84	(-35.10,-22.59)*
	Step width			-0.49	(-0.87, -0.12)‡
	R^2		0.35		0.49
DSP (sec)	Step width	0.02	(0.01, 0.02)*	0.02	(0.01,0.03)*
	R^2		0.11		0.11

Notes: * $p < 0.05$;
β = regression coefficient; CI = confidence intervals; DSP = double support phase

Figures 1 and 2 summarise the results from the gait and sensorimotor analysis and the gait pathway modelling. These results describe a possible pathway of the gait variables culminating in gait speed for men and women. Figures 1 and 2 summarise these pathways, extending the results from the analysis of the associations between sensorimotor factors and the gait measures that were presented in the chapter.

These cross-sectional results suggest that a wider step width results in a longer DSP, which in turn results in a shorter step length and slower cadence. Wider steps may lead to a longer DSP because there is a larger medio-lateral distance to shift the weight over to a single foot. In the same way the larger medio-lateral distance covered might result in less forward progression and shorter steps. These changes may be part of a strategy to increase stability whilst walking in response to poor functioning in the sensorimotor systems. Alternatively these changes could be due insufficient muscle strength or processing speed to generate a faster and more efficient gait pattern.

Figure 1 MEN

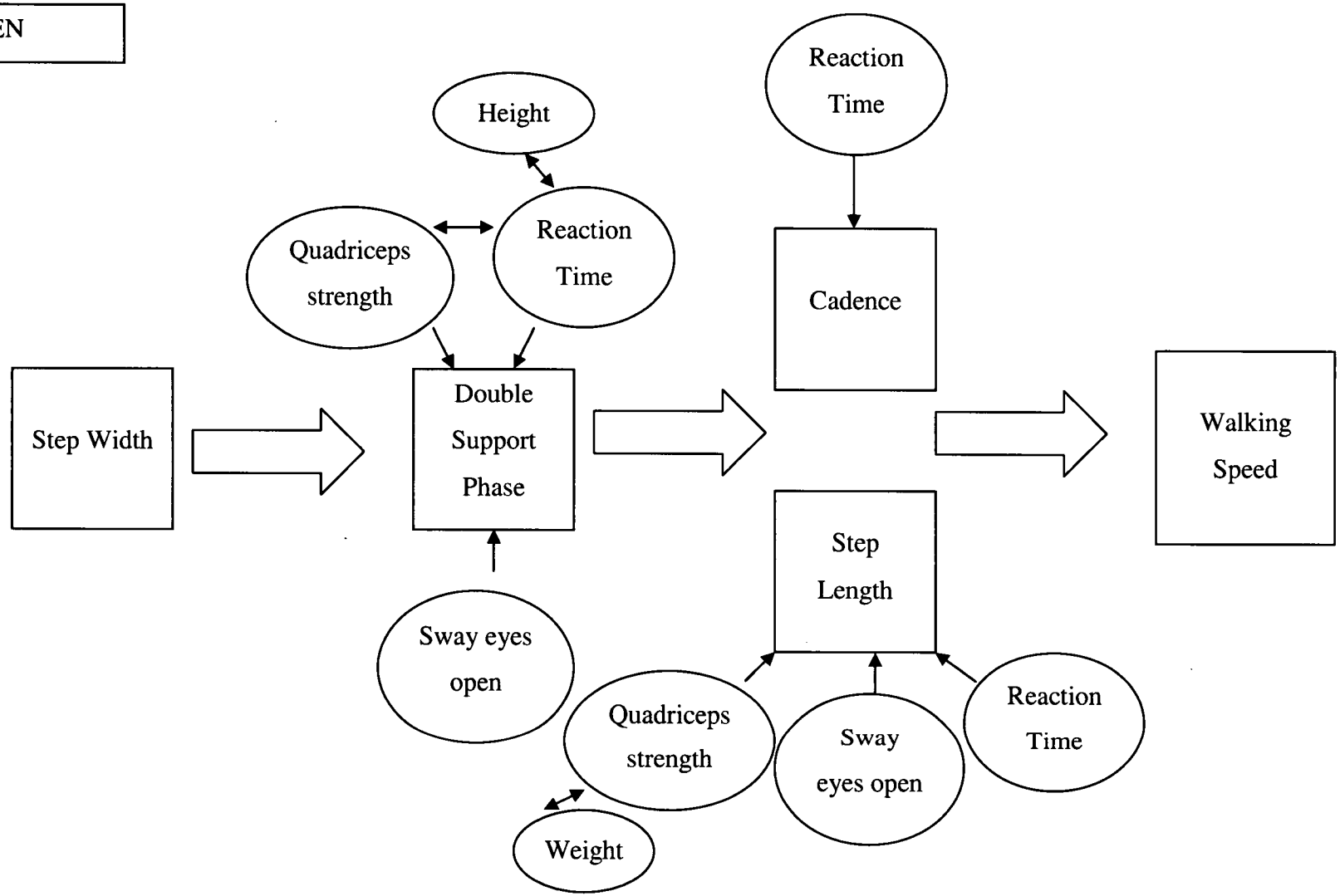
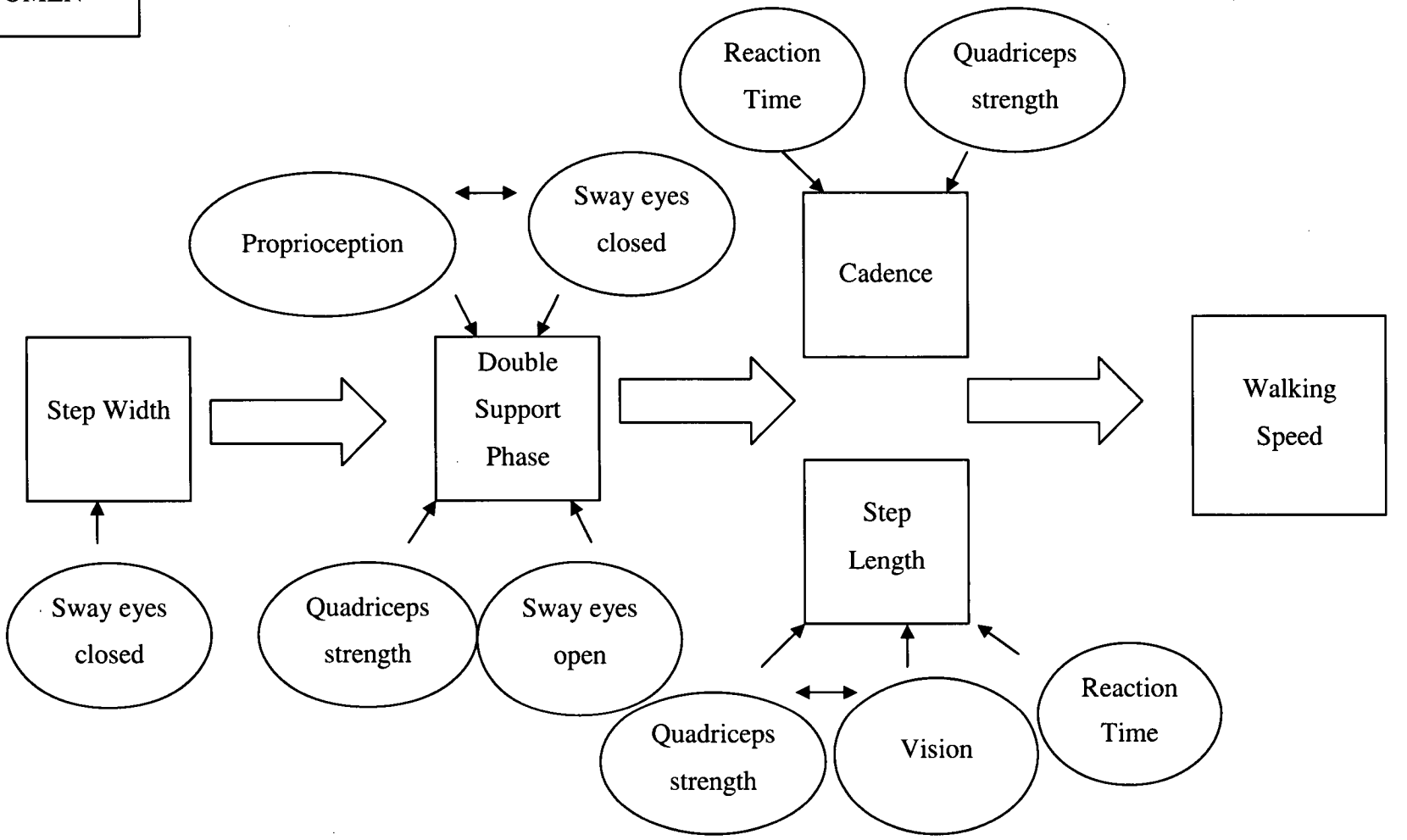

Reaction Time
Height
Quadriceps strength
Reaction Time
Cadence
Step Width
Double Support Phase
Walking Speed
Step Length
Sway eyes open
Quadriceps strength
Sway eyes open
Reaction Time
Weight

Figure 2 WOMEN



These results may provide specific sensorimotor targets for intervention on each gait measure, and may prove useful in clinical practice. Furthermore these results suggest that interventions to improve one gait measure will have beneficial effects on other aspects of gait performance. For example, successful interventions to improve DSP can be expected to also result in improved step length and cadence.

References

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Appendix 6B: Sensorimotor factors did not contribute to the curvilinear relationship between gait speed and advancing age for women

The cross-sectional analysis of the association between gait speed and age reported in chapter 4 identified accelerated slowing of gait speed for older women. This may have put them at greater risk of adverse events such as loss of independence, falls and need of admission to residential care [1, 2]. This appendix reports the results of an investigation of whether sensorimotor factors contributed to the curvilinear relationship between gait speed and advancing age for these women.

The sample for this investigation were women aged between 60-86 years (n=124) randomly selected from the Southern Tasmanian electoral roll. This sample is described in Chapter 6. Participants were included if they could walk without a gait aid and could understand simple commands in English. They were excluded if they resided in a nursing home or had any contraindications to Magnetic Resonance Imaging (MRI) scan. The Southern Tasmanian Health and Medical Human Research Ethics Committee approved this study and written consent was obtained from all participants.

Regression analysis was used to determine whether the addition of sensorimotor measures removed the curvilinear association between gait speed and age. Sensorimotor measures - postural sway (with eyes open and closed on a foam mat), reaction time, quadriceps strength, proprioception, visual contrast sensitivity - were added to the model in turn.

The characteristics of the women are reported in Table 6.1. Adjusting for height and weight, the association between age and gait speed was curvilinear (p=0.004). Table 1 shows the effect of the addition of each sensorimotor factor on this association. The variation in the cross-sectional effect of an additional year of age between women aged 65 and 85 reduced with the inclusion of each sensorimotor factor. However, even after the addition of all the sensorimotor factors the association between age and gait speed remained curvilinear (p=0.024).

Table 1 The cross-sectional effect of the additional year of age on gait speed showing the limited effects of adjusting for sensorimotor function

Model	Adjusted for	Regression coefficients for age (β): At age 65 years β (95% CI)	At age 75 years β (95% CI)	At age 85 years β (95% CI)	p-value*
1	Height and weight	0.29 (-0.71,1.30)	-1.62 (-2021,-1.04)	-3.54 (-5.26,-1.82)	0.004
2	Model 1 + SEC	0.21 (-0.78,1.20)	-1.40 (-2.02,-0.79)	-3.02 (-4.79,-1.25)	0.015
3	Model 2 + Reaction time	0.19 (-0.79,1.17)	-1.37 (-1.98,-0.77)	-2.94 (-4.69,-1.19)	0.017
4	Model 3 + Quadriceps strength	0.33 (-0.63,1.28)	-1.11 (-1.73,-0.49)	-2.55 (-4.27,-0.83)	0.024
5	Model 4 + SEO	0.40 (-0.55,1.35)	-1.03 (-1.65,-0.42)	-2.47 (-4.18,-0.76)	0.024
6	Model 5 + Proprioception	0.40 (-0.56,1.35)	-1.02 (-1.64,-0.40)	-2.44 (-4.16,-0.72)	0.026
7	Model 6 + Visual contrast sensitivity	0.49 (-0.49,1.47)	-0.95 (-1.60,-0.31)	-2.39 (-4.12,-0.67)	0.024

Notes: SEC=Postural sway with eyes closed; SEO= Postural sway with eyes open

*P-value from test of the coefficient of the age^2 term in a linear regression of gait speed on age with adjustment for the other factors listed in column two.

These results indicate that the curvilinear relationship between age and gait speed for women is not entirely explained by poorer performance in sensorimotor functioning. Adjusting for the sensorimotor factors reduced but did not remove the variation in the cross-sectional effect of an additional year of age between younger and older women. Further research is needed to investigate other factors that may contribute to the accelerated change in gait speed with advancing age seen for women in this study.

References

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Chapter 7: Sensorimotor factors affecting gait variability in older people - A population-based study

7.1 Preface

In previous chapters it has been shown that gait performance (Chapter 4) was poorer, and variability in gait performance (Chapter 5) was greater, among the oldest subjects in samples from the study population of community dwelling 60-86 year olds. Chapter 6 then reported on the results of an investigation of whether impaired sensorimotor function accounted for the associations of average measures of gait with age, with the finding that the sensorimotor factors were associated with gait independently of age. These associations did not appear to be the result of chronic disease. That investigation is extended in this chapter to measures of variability in gait. The cross-sectional associations of variability in step time, double support phase, step length and step width with sensorimotor factors are examined in a population-based sample of 412 persons. The purpose of the study was to identify factors that might be useful in intervention programs to reduce gait variability. The text of this chapter has been published [1].

7.2 Introduction

The prevalence of walking problems is reported to be as high as 35% in older adults [2]. The inability to walk safely may lead to falls, hospitalisation and loss of independence [3]. Gait variability, the intra-individual fluctuation in a gait measure (such as step time variability) from one step to the next, may be a more sensitive predictor of falls risk and mobility impairment than averaged measures such as mean step time [4-6]. Gait variability in step width, step length, step time and double support time (DST) increases with advancing age [7]. Although cerebral disease has been linked to gait variability [8, 9], little is known about the contribution of clinically identifiable sensorimotor abilities.

Sensorimotor functions such as muscle strength, balance, reaction time, vision and proprioception decline with advancing age [10] and it is possible that these functions may play a role in determining gait variability. A better understanding of modifiable sensorimotor factors that predict increased gait variability could be of use in designing intervention programs to reduce gait variability and possibly falls risk. Few studies have been conducted to examine these relationships [5, 11-14]. In these, poorer

strength, balance and processing speed are reported to be associated with greater stride and stance time variability [5, 11, 14], poorer strength and processing speed with greater step length variability [13, 14], and poorer balance and paradoxically better vibration sense with increased step width variability [12, 14]. Although informative, these studies are limited by the use of small convenience based samples [5, 11-13], the use of only univariable analyses [5, 13], and the inclusion of only individual sensorimotor measures [12]. Gait variability is highly likely to be determined by many factors [11] and therefore it is appropriate to explore the combined effects of such factors and minimise the possibility of confounding by extraneous factors such as age and body size. Furthermore, there has been only one population-based study examining this topic [14] but with several limitations. This study relied on self reported, ranked or indirect measurements of sensorimotor factors, with potential consequent measurement bias or imprecision of estimates. In addition measures of balance were not included, despite others suggesting that step width and double support time variability might represent balance control during gait [15].

In a population-based sample of older people, we aimed to study whether a range of sensorimotor abilities were independently associated with several measures of temporal and spatial gait variability. We hypothesised that poorer performance in these sensorimotor measures would be associated with greater gait variability.

7.3 Methods

Participants

The study sample consisted of participants aged 60 to 86 years (n=412) randomly selected from the Southern Tasmanian electoral roll. Recruitment procedures have been detailed previously [16]. Participants were included if they were able to walk without the use of a gait aid and excluded if they lived in a nursing home, were unable to follow simple commands in English or had any contraindications to magnetic resonance imaging as this was part of the larger study. The Southern Tasmanian Health and Medical Human Research Ethics Committee approved this study and written consent was obtained from all participants. All physical measurements were performed during the same visit.

Gait Analysis

Temporal (step time, DST) and spatial (step length, step width) gait variables were measured at preferred speed using a 4.6 metre computerised mat with embedded

pressure sensors (*GAITRite* system; CIR System; Clifton, NJ). Step width was calculated as the perpendicular distance from heel centre of one footprint to the line of progression formed by two footprints of the opposite foot. These variables were selected as they have been examined in previous studies of falls risk [6, 17, 18] and represent both temporal and spatial measures and in both the frontal and sagittal planes. Participants performed six walks starting and finishing two metres before and after the mat to allow for acceleration and deceleration. As in previous studies, the standard deviation of the mean of all steps recorded in six walks was used to represent variability of each measure [4-6, 14, 19].

Sensorimotor Factors

Sensorimotor function was assessed using the short form of the Physiological Profile Assessment (PPA) which has been described previously [20]. The PPA is a validated battery of the following sensorimotor measurements [21]: (1) Visual contrast sensitivity (VCS) (dB); (2) lower limb proprioception (degrees); (3) Maximal isometric quadriceps strength (kg); (4) Simple reaction time (ms); (5) Postural sway (mm) using a sway-meter that measures displacement of the body while standing on foam with eyes open (SEO) and closed (SEC). Poorer performance is indicated by lower scores of VCS and quadriceps strength, higher scores of proprioception, longer reaction time and greater displacement in body sway. The reliability of the items on the PPA ranges from moderate to excellent [21].

Other Measurements

Height (cm), weight (kg) and self-reported history of lower limb arthritis, stroke, Parkinson's disease, dementia, hypertension, diabetes mellitus and falls (in the preceding 12 months) were recorded using a standardised questionnaire to characterise the study population. Mood was measured using the Geriatric Depression Scale (short version) [22] and functional dependence using the Lawton's Instrumental Activities of Daily Living Scale (brief version) [23]. Executive function and cognitive speed were measured using the Victoria Stroop test [24] and the Digit-Symbol coding subtest of the Wechsler Adult Intelligence scale – Third Edition [25]. Non-responders also completed a brief phone interview providing their medical history and history of falls in the previous 12 months to estimate potential non-response bias.

Data Analysis

As there were no differences between left and right gait variability measures ($p>0.05$), we used the average of the measures of the two sides in further analyses. Spearman correlations were first used to estimate the relationships between variables. Multivariable linear regression was used to model the effect of each sensorimotor factor on individual gait variability measures firstly adjusting for age, sex, height and weight. We further adjusted the models for gait speed because it has been postulated that speed may affect variability [26]. In the final models for each sensorimotor factor, additional adjustment was made for other sensorimotor factors and relevant covariates. Statistical interaction between covariates was assessed by including the product of those covariates as terms in the regression. Two women were excluded from analysis, one because of influential extreme high values in step time, step width and DST variability, and the other because she was unable to complete testing due to significant cognitive disability. Analyses were conducted using STATA version 9.0 (StataCorp, College Station, TX).

7.4 Results

The sample response proportion was 51% (412/804). Non-responders were older ($p=0.01$) and were more likely to report hypertension ($p=0.03$) but did not differ from responders with respect to sex or other medical history.

Demographic, medical and gait characteristics are summarised in Table 7.1. The mean age of the sample was 72 (SD 7.0) years, with 42.9% being female. The mean walking speed was 113.9 cm/sec, with a mean of 27.3 (*SD* 5.4) steps recorded per person.

Correlation coefficients are provided in Table 7.2. Poorer performance in VCS, proprioception, SEO and SEC were associated with greater variability in all gait measures. Slower reaction time was associated with greater variability in all measures except step width. Poorer quadriceps strength was associated with greater variability in temporal, but not spatial variability measures. Associations between the gait variability measures ranged from 0.15-0.51. The associations between sensorimotor factors and each of the gait variability measures adjusted for covariates are summarised as regression coefficients in Table 7.3.

Table 7.1 Sample characteristics (n=410)

Characteristic	
Age, mean(SD)	72.0 (7.0)
Height [cm], mean (SD)	167.0 (9.0)
Weight [kg], mean (SD)	77.9 (15.1)
Medical History, n (%)	
Hypertension	202 (49.3)
Diabetes	50 (12.2)
Stroke	34 (8.3)
Parkinson's Disease	2 (0.5)
Dementia	2 (0.5)
Arthritis	181 (44.4)
Self report falls in previous 12 months	68 (16.6)
Other	
Geriatric depression scale (short version), mean (SD)	2.05 (2.32)
Independent in Activities of Daily living (%)	97.5
Gait characteristics, mean (SD)	
Speed (cm/sec)	113.90 (20.90)
Step time (s)	0.55 (0.05)
Step length (cm)	61.73 (9.09)
DST (s)	0.25 (0.06)
Step width (cm)	9.99 (2.94)
Variability gait characteristics, mean (SD)	
Step time variability (ms)	21.77 (10.67)
Double support time variability (ms)	20.40 (7.76)
Step length variability (cm)	2.72 (0.92)
Step width variability (cm)	2.12 (0.69)
Sensorimotor variables, mean (SD)	
Visual contrast sensitivity (dB)	20.69 (2.17)
Reaction time (ms)	232.13 (41.77)
Proprioception (degrees)	1.56 (1.23)
Quadriceps strength (kg)	32.03 (11.97)
Sway eyes open (mm)	21.15 (12.98)
Sway eyes closed (mm)	48.17 (43.53)

SD=standard deviation

Table 7.2 Spearman correlations between sensorimotor and gait variables (n=410)

	Age	Gait Speed	Step time Variability (ms)	DST Variability (ms)	Step length Variability (cm)	Step width Variability (cm)
Age (years)	-	-0.37*	0.27*	0.27*	0.22*	0.17†
Gait speed (cm/sec)	-	-	-0.59*	-0.53*	-0.20*	-0.05
VCS(dB)	-0.43*	0.22*	-0.22*	-0.18*	-0.15†	-0.13†
Reaction time (ms)	0.17†	-0.35*	0.18*	0.21*	0.11‡	-0.00
Proprioception (degrees)	0.12‡	0.09	0.15†	0.18*	0.13†	0.12‡
Quadriceps strength (kg)	-0.33*	0.37*	-0.18*	-0.18*	-0.00	-0.02
Sway eyes open (mm)	0.29*	-0.25*	0.18*	0.13†	0.17†	0.17†
Sway eyes closed (mm)	0.34*	-0.20*	0.28*	0.23*	0.16†	0.21*
Step time Variability (ms)	-	-	-	0.51*	0.40*	0.17†
DST Variability (ms)	-	-	-	-	0.37*	0.15‡
Step length Variability (cm)	-	-	-	-	-	0.18†

Notes: *$p<0.001$; †$p<0.01$; ‡$p<0.05$;
VCS=Visual contrast sensitivity; DST=Double support time

Table 7.3 Associations between gait variability (outcome) and sensorimotor factors adjusted for covariates (n=410)

	Step time variability (ms)		DST variability (ms)		Step length variability (cm)		Step width variability (cm)	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
	β (95 % CI)	β (95 % CI)	β (95 % CI)	β (95 % CI)	β (95 % CI)	β (95 % CI)	β (95 % CI)	β (95 % CI)
VCS (dB)	-0.344	-0.178	-0.240	-0.091	-0.028	-0.022	-0.004	-0.004
	(-0.641,-0.048)‡	(-0.435,0.080)	(-0.529,0.048)	(-0.348,0.166)	(-0.064,0.007)	(-0.058,0.014)	(-0.033,0.025)	(-0.033,0.025)
Reaction time (ms)	0.025	0.001	0.031	0.011	0.003	0.002	0.000	0.000
	(0.010,0.040)†	(-0.012,0.016)	(0.017,0.045)*	(-0.00,0.024)	(0.001,0.004)†	(0.000,0.004)‡	(-0.001,0.002)	(-0.001,0.002)
Proprioception (degrees)	0.566	0.350	0.799	0.611	0.023	0.015	0.041	0.041
	(0.038,1.090)‡	(-0.090,0.791)	(0.299,1.298)†	(0.177,1.045)†	(-0.037,0.083)	(-0.044,0.074)	(-0.008,0.087)	(-0.007,0.090)
Quadriceps strength (kg)	-0.091	0.001	-0.038	0.054	-0.002	0.002	-0.001	-0.001
	(-0.154,0.027)†	(-0.048,0.067)	(-0.100,0.024)	(-0.029,0.112)	(-0.009,0.006)	(-0.006,0.010)	(-0.007,0.089)	(-0.007,0.005)
Sway eyes open (mm)	0.055	0.001	0.036	-0.012	0.008	0.006	0.003	0.004
	(0.007,0.103)‡	(-0.040,0.043)	(-0.001,0.081)	(-0.053,0.029)	(0.002,0.013)†	(0.000,0.012)‡	(-0.001,0.008)	(-0.001,0.008)
Sway eyes closed (mm)	0.035	0.021	0.030	0.017	0.003	0.002	0.004	0.004
	(0.020,0.050)*	(0.008,0.034)†	(0.016,0.044)*	(0.005,0.030)†	(0.001,0.004)†	(0.000,0.004)‡	(0.002,0.006)*	(0.002,0.007)*

Notes: $^{*}p<0.001$; $^{\dagger}p<0.01$; $^{\ddagger}p<0.05$
Model 1 – adjusted for age, sex, height and weight; Model 2 – Model 1 + gait speed
VCS= visual contrast sensitivity; DST=Double support time

After adjusting for age, sex, height and weight (model 1), poorer performance on all sensorimotor measures was associated with greater step time variability. Poorer performance in reaction time, proprioception and SEC were associated with greater DST variability. Greater sway (eyes open and closed) and slower reaction time were associated with greater step length variability. Only greater displacement in SEC was associated with greater step width variability. After the addition of gait speed (model 2), there was a marked reduction in the magnitude of the association between sensorimotor factors and temporal variability measures (range of reduction in coefficients 24-100%), such that the majority of the associations were no longer significant. Gait speed was not included in the final model (Table 7.4) for temporal gait measures because, based on these results and on physiological grounds, we could not exclude the possibility that gait speed was an intermediate in the relationship between sensorimotor factors and temporal gait variability. Adjustment for gait speed only modestly reduced the strength of the associations of sensorimotor factors with spatial variability measures (range of reduction in coefficients 0-34%) and hence was retained in the final models.

When sway measures were added to the final models (Table 7.4) they remained essentially unchanged except that larger displacement in SEC was associated with greater variability in all measures and the association between reaction time and step length variability was no longer significant. VCS and sway eyes open were not significantly associated with any of the gait variability measures. There were no significant interactions between any of the covariates. Adjusting for executive function and cognitive speed made no difference to the results except for the association of the reaction time task of the PPA with step time variability which was largely attenuated by inclusion of these cognitive tasks. Reaction time appeared to be a proxy for central processing speed and mental flexibility in this relationship, and was therefore not included in the final model. Adjusting the results for the Geriatric Depression score suggested that poorer mood may be an intermediate in the associations of reaction time and quadriceps strength with step time variability, and was therefore also not included in the final model. The strength of the associations between sensorimotor measures and each gait variability measure are also summarised in Table 7.4 as partial R^2 values from the final multivariable models. The models explained 11-19% of the variance in gait variability.

Table 7.4 Multivariable associations between gait variability (outcome) and sensorimotor factors (n=410)

Gait measure	Predictor variable	β (95 % CI)	p value	Partial R^2
Step time variability (ms)*	Sway eyes closed	0.031 (0.016,0.046)	<0.001	0.04
	Reaction time	0.015 (0.005,0.030)	0.042	0.01
	Quadriceps strength	-0.071 (-0.134,-0.007)	0.028	0.01
	R^2	0.16		
DST variability (ms)*	Sway eyes closed	0.023 (0.009,0.037)	0.001	0.02
	Reaction Time	0.024 (0.010,0.038)	0.001	0.02
	Proprioception	0.660 (0.179,1.142)	0.007	0.01
	R^2	0.19		
Step length variability (cm)*†	Sway eyes closed	0.002 (0.000,0.004)	0.014	0.01
	R^2	0.14		
Step width variability (cm)*†	Sway eyes closed	0.004 (0.002,0.007)	<0.001	0.03
	R^2	0.11		

Notes: The reported R^2 value is for the model adjusted for covariates
*All models adjusted for age, sex, height, weight and other significant sensorimotor factors
†Also adjusted for gait speed
DST=Double support time

7.5 Discussion

In this population-based study, we investigated the effect of a range of important sensorimotor functions on several measures of gait variability. Poorer postural sway (eyes closed, standing on a foam mat) was independently associated with greater variability in all gait measures. Slower reaction time was associated with greater variability in temporal measures (step time and DST variability), weaker quadriceps strength was associated with greater step time variability and poorer proprioception was associated with greater DST variability. These results provide evidence that sensorimotor factors may impact differently on gait variability, albeit with some common effects, thus adding to the theoretical knowledge of mechanisms underlying gait control. They also provide insights into which factors may be potentially modified to improve gait variability and thus possibly reduce the risk of mobility decline and falling in older people.

Postural sway (SEC) was consistently associated with all measures of gait variability and explained the greatest proportion of their variance. In contrast, previous investigators have reported quadriceps strength as the strongest predictor of gait speed [20, 28], indicating

that gait speed and gait variability may have different underlying mechanisms. These reported differences may contribute to the understanding of why measures of gait variability, but not gait speed, are predictors of falls in some populations [5, 6]. The exact mechanisms underlying the association between SEC and gait variability measures are unknown. SEC is a static test of postural control that measures a participant's ability to maintain the centre of gravity within the limits of the base of support when standing on a foam mat with the eyes closed. Poorer performance on such a test may result in difficulty maintaining stability in a more dynamic and complex activity such as walking, where the body is in motion and the centre of gravity is outside the base of support for much of the gait cycle [29]. The SEC test is also thought to measure the ability of the vestibular system to maintain postural stability after the reduction of proprioceptive and visual input [30]. Age or disease related decline may result in a less reliable vestibular system that is unable to compensate for reduced sensory information, potentially leading to increased sway [10, 31]. Altering the timing and length of steps during walking may be an attempt to regain one's balance or alternatively an attempt to stabilise vision when there is poor underlying postural control [32]. Interestingly SEO, a condition where both vision and the vestibular system are available to maintain balance, was not independently associated with gait variability in the final models. This may indicate some aspects of vision are particularly important to maintain a regular gait pattern in older adults. Alternatively SEC may simply represent a more complex task where the body is unable to compensate for reduction in two senses [30].

Our findings support the prior suggestion that step width and DST variability represent balance ability whilst walking [15], but also indicate step length and step time variability may also represent this concept. This is consistent with other smaller studies that have found measures of balance are associated with greater step width [12] and temporal variability measures [5, 11]. However this is the first study to find postural sway is also associated with step length variability.

Longer reaction time, a measure of processing speed [28], was associated with greater temporal variability, but not spatial variability. The body's inability to adequately process incoming sensory and outgoing motor information in a timely manner may lead to inconsistent and inaccurate foot placement. It has previously been suggested that those measures that have a timing component may explain the stronger associations with temporal measures [14]. Adjusting our results for cognitive measures reduced the association between reaction time and step time variability by more than one half,

suggesting that reaction time might be a proxy for these cognitive measures. Our results are in agreement with most other studies that report tests representing processing speed are associated with temporal variability measures [14, 33]. Although we could not reproduce a previous finding of an independent association of processing speed with step length variability [14], reaction time was associated with this measure before the addition of SEC. Adjusting for the Geriatric Depression scale reduced the association between reaction time and step time variability by one third, raising the possibility it may be an intermediate in this association but without excluding a role as a confounder. These results suggest that, in the latter case, exercises to improve reaction time may need to be part of a multi-factorial intervention program to reduce step time variability.

Our study is in agreement with others that have reported a relationship between muscle strength and step or stride time variability [5, 11]. Interestingly our study also agrees with the study by Brach et al [14] that muscle strength is not associated with step width or step length variability measures. Although muscle strength was assessed differently in their study, these findings add weight to the suggestion that gait variability measures are not homogeneous [14].

The association between poorer proprioception and greater DST variability suggests proprioceptive feedback is required to maintain consistent timing in double support phase. Proprioception was also individually associated with step time variability but when the other sensorimotor variables were added its effect was no longer significant ($p=0.08$).

We hypothesised that poorer performance in all sensorimotor measures would be associated with increased gait variability. However VCS and SEO were not independent predictors of any of the gait variability measures. In contrast to our study Brach et al reported poorer performance on a self reported test of vision was associated with decreased step width variability [14]. This may have been due to their different method for calculation of step width.

This study adds significantly to knowledge of sensorimotor factors associated with gait variability. It is one of the few studies providing data on both temporal and spatial gait measures and a range of quantitative sensorimotor factors, with careful attention to evaluating the independent contributions of the sensorimotor factors. These factors can potentially be modified or compensated for through exercise programs, education or provision of a mobility aid and could therefore be targets for interventions aimed at reducing gait variability [34]. Being population-based, this study also provides results that

are more generalisable than those from smaller convenience samples used in the majority of previous studies. However, although there were few differences between responders and non-responders the sample is likely to be healthier than the general population as shown by their high levels of independence in activities of daily living. Furthermore the sensorimotor factors used in this study explained only a small but meaningful amount [35] of the variance in gait variability. It is also possible that other measures of sensorimotor function, such as quadriceps power, joint range of movement, strength of other key muscle groups or more sensitive measures of vestibular function may have resulted in stronger associations. Further research is needed to determine if the inclusion of these and additional factors such as other cognitive measures or subclinical cerebral changes [14, 36, 37] are able to explain more of the variance. Another limitation of this study is that small numbers of steps were collected over six trials. This prohibited analysis of long range correlations in the data and may have affected the reliability of the measures [38]. To overcome this we used a greater number of trials in a large sample. In addition, the number of steps, although small were in accordance with recommendations [39] and served to avoid participant fatigue. These findings are also limited by their cross-sectional nature, and need to be repeated in longitudinal and intervention studies to address causality in relationships.

Summary

Greater postural sway was associated with greater variability in all gait measures. Slower reaction time was associated with greater variability in temporal gait measures. Poorer quadriceps strength was associated with step time variability and proprioception was associated with greater DST variability. Further research is warranted to determine if inclusion of these factors in intervention programs reduces gait variability, disability and falls risk in older adults.

7.7 Postscript

The findings of this chapter - that poorer performance in postural sway, reaction time, proprioception and quadriceps strength are associated with greater variability in specific gait measures - may provide useful additional information for the design of intervention programs to improve gait and reduce the occurrence and impact of associated adverse events. However, adjusting for sensorimotor factors reduced but did not fully account for the association of gait variability with age.

One type of adverse event, which is common in older age, is episodes of loss of balance resulting in falls. It is not yet known which gait and gait variability measures best predict those at increased risk of falling. The following chapter investigates whether poorer performance in the gait and gait variability measures increase the risk of single or multiple falls by older people.

7.8 References

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Chapter 8: Gait, gait variability and the risk of multiple incident falls in older people - A population-based study

8.1 Preface

The results of the studies reported in Chapters 4 and 5 of this thesis showed that poorer performance in gait and gait variability measures is more common among older people. Chapters 6 and 7 reported the findings of studies that identified a number of sensorimotor factors that were associated with poorer performance on gait and gait variability measures, with different sensorimotor factors associated with different gait measures independently of age. The results provide important information on which to base trials of interventions to prevent walking decline in older people. However there remains the unanswered question of whether these changes to gait patterns increase the risk of falls. The aim of this chapter is to examine whether poorer performance in the gait and gait variability measures described in the previous studies of this thesis increase the risk of single or multiple falls among 60-86 year old people. The text of this chapter has been submitted for publication [1].

8.2 Introduction

Falls are a major public health problem for older people and society. For the individual, falls are associated with loss of confidence, functional dependence, injury, and admission to residential care [2, 3]. Furthermore with the aging of populations, the costs of falls are rapidly increasing [4]. It is essential that those at risk are identified early so that adequate treatment and prevention programs can be implemented.

Many falls in older people occur due to a complex interaction between intrinsic and extrinsic factors. Intrinsic factors are attributable to the person, such as poor muscle strength and cognition. Extrinsic factors are those related to the environment, such as poor lighting or obstacles that are tripped over. Evidence suggests that the greater the number of intrinsic impairments, the greater the risk of falling [2, 5]. Inability to compensate for age- or disease-related decline in one or more such intrinsic factors may lead to impaired gait [6, 7]. Measures of gait may therefore be useful surrogates of an older person's risk of falling.

It is uncertain as to which measures of gait best predict those who are likely to fall. Previous results are conflicting as to whether temporal-spatial measures such as slower gait speed [5, 6, 8-14], shorter steps [6, 8, 10-13] and longer double support phase (DSP) [8, 10, 11] are associated with falls or not. Although it has been postulated that gait variability (intra-individual fluctuation in a gait measure from one step to the next) may be more promising than average measures of gait in predicting falls risk [11, 13], there is again no consensus as to which measures of variability are most useful [6, 10-13, 15].

The majority of previous studies in this field have been limited by small samples of volunteers or patient groups [8, 11, 12, 16-20] and retrospective ascertainment of falls with potential for recall bias [13, 15, 16, 18, 20]. In the only prospective population-based study that included both men and women, falls risk was predicted by slower gait speed, longer swing and DSP, and greater variability in swing time and stride length [10]. Other gait measures such as step width and its variability, which may also be associated with falls [11, 13, 15] were not studied. Moreover, the authors chose to analyse all fallers together, when previous studies indicate that those who fall only once are likely to have different underlying mechanisms than those who fall multiple times [5, 21].

We hypothesised that poorer performance in a range of gait and gait variability measures would be independently associated with a greater risk of multiple falls after taking into account other factors capable of influencing gait and falls.

8.3 Methods

Participants

People aged between 60 and 86 years (n=412), who were residents of southern Tasmania, were randomly selected from the Tasmanian electoral roll. Participants were included if they could walk without the use of a gait aid. Exclusion criteria were living in a high-care residential facility or any contraindications to MRI scan (a requirement for the overall study). The Southern Tasmanian Health and Medical Human Research Ethics Committee approved this study and written consent was obtained from all participants.

Gait

Gait measures were collected with a 4.6 metre computerised walkway system (*GAITRite*, CIR systems, USA). Gait speed, step length, step time, cadence, DSP and step width were collected over six trials at preferred walking speed. Participants started walking two metres before the mat, and continued two metres past the mat, to allow for acceleration and

deceleration. Variability in step length, step time, DSP and step width were calculated as the standard deviation of all steps for the respective measure from the six trials.

Falls

A fall was defined as 'an unexpected event in which the participant comes to rest on the ground, floor, or lower level' [22]. Participants were asked to complete a falls calendar for a 12 month period following baseline gait measurement, and were also sent a falls questionnaire with a reply paid envelope every two months to record information about falls that had occurred in those periods. Those who fell more than once during the 12 month follow-up were classified as having multiple falls. The outcome variable for analysis was therefore a variable with three levels (no falls, single falls and multiple falls).

Other measures

A standardised questionnaire was used to obtain information about self-reported medical history (lower limb arthritis, hypertension, diabetes mellitus, stroke, dementia and Parkinson's disease). Non-responders completed a brief phone interview providing similar details about their medical history.

The following were chosen as possible confounders: height and weight; sensorimotor factors (reaction time, quadriceps strength, proprioception, visual contrast sensitivity, body sway on a foam mat with the eyes open and closed) measured in accordance with the protocols of the of the Physiological Profile Assessment [23]; the Victoria Stroop test [24] and the Digit Symbol Coding subtest of the Wechsler Adult Intelligence Scale – Third Edition [25] as measures of executive function and processing speed; mood measured using the Geriatric Depression Scale (short version) [26]; counter and prescribed medications with participants subsequently classified as taking four or more prescribed medications, any blood-pressure lowering medication, or any psychoactive medication.

Statistical Analysis

Chi-squared analysis (χ^2) and t-tests were used to compare responders and non-responders. Log multinomial regression [27] was used to estimate risk and relative risk (RR) of single and multiple falls. The continuous gait measures (study factors) were divided into quarters to more clearly quantify the associations. For a study factor classified into four levels, RR is the proportion of subjects with the outcome at one of the other three levels of the study factor relative to the proportion of subjects with the outcome factor in the reference level of the study factor. All models were adjusted for age, sex, height and

weight. Further adjustment was made firstly for sensorimotor or cognitive factors, and secondly for mood or medication usage, if the relevant variable changed the coefficient of the gait measure by more than 10% [28]. Finally, for the gait variability measures, additional adjustment was made for gait speed to determine its effect on the associations. Interactions were examined between age or sex and each gait measure. Linear trend was assessed by tests of the statistical significance of the coefficient of a single predictor for each study factor with the four levels coded as -3,-1, 1 and 3. Quadratic trend was assessed by adding a predictor for the square of that variable and testing the significance of its coefficient. Because a threshold value was detected for gait speed, receiver operator curves (ROC) and sensitivity and specificity analyses were calculated to determine how well a dichotomised variable of gait speed classified participants. Data were analysed using STATA version 10.1 (StataCorp, Texas USA).

8.4 Results

The participant response proportion at enrolment was 51% (412/804). Responders were younger (p=0 .01) with a lower self reported history of hypertension (p=0.03) than non-responders. One participant was unable to continue after a medical event, and was excluded, leaving 411 participants in the study. Of the baseline sample, 83% (n=342) completed all six falls questionnaires and 96% (n=393) completed at least five questionnaires. If a participant had not completed all six questionnaires and had not reported a fall (n=50), they were classified as lost to follow up, leaving 361(88%) participants to include in the analysis of falls. During follow-up, 43.5% (n=157) of participants reported a fall, with a higher percentage of women (50%, n=77) than of men (39%, n=80) reporting a fall. A single fall was reported by 25.2% (n=91) and multiple falls by 18.3% (n=66) of participants. Table 8.1 provides baseline characteristics for those lost to follow up, and those with no falls, one fall or multiple falls (Appendix 8A provides baseline characteristics for the overall sample and those included in the analysis of fall). Those lost to follow up walked with slower gait speed (p=0.002), shorter steps (p=0.007) and had a longer DSP (p<0.001) compared to those included in the analysis. There were no other significant differences between those lost to follow-up and those included in analyses.

Gait and the relative risk of falls

Table 8.2 (gait measures) and Table 8.3 (gait variability measures) present the final adjusted relative risks of single and multiple falls. None of the gait or gait variability

measures was associated with the risk of single falls. After initial adjustment for age, sex, height and weight, the risk of multiple falls was associated with greater DSP variability (p=0.01) and greater step length variability (p=0.02), and non-significant trends were observed for slower gait speed (p=0.05) shorter step length (p=0.06) and larger DSP (p=0.07).

Table 8.1 Sample characteristics (n=411)

Characteristic	Lost to follow up n=50	No falls n=204	Single Fall n=91	Multiple Falls n=66
Age, mean (SD)	72.6 (7.0)	71.2 (6.8)	72.3 (6.2)	73.92 (8.4)
Height in cm, mean (SD)	167.6 (9.6)	167.9 (8.7)	166.0 (9.4)	165.0 (8.7)
Weight in kg, mean (SD)	80.2 (16.2)	81.2 (16.8)	77.4 (14.3)	75.7 (75.7)
Medical History (self reported), n (%)				
Arthritis	26 (52)	76 (37)	49 (54)	31 (47)
Hypertension	22 (44)	95 (47)	50 (55)	36 (55)
Diabetes	6 (12)	24 (12)	14 (15)	6 (9)
Stroke	2 (4)	17 (8)	8 (9)	8 (12)
Parkinson's disease	0 (0)	1 (0.5)	0 (0)	1 (2)
Dementia	0 (0)	0 (0)	0 (0)	2 (3)
Gait measures, mean (SD)				
Gait speed, cm/sec	105.1 (22.7)	118.0 (19.4)	113.0 (19.3)	107.9 (24.9)
Cadence, steps/min	107.9 (11.7)	111.3 (9.5)	110.4 (8.9)	109.7 (12.1)
Step length, cm	58.3 (10.01)	63.6 (8.4)	61.3 (9.1)	58.6 (10.2)
DSP, %	25.3 (3.5)	22.4 (3.4)	23.1 (3.5)	24.0(4.6)
Step width, cm	10.2(2.4)	9.8 (2.9)	10.1 (2.9)	10.2 (3.5)
Step time variability, ms	23.33 (8.97)	20.66 (9.78)	22.03 (18.44)	26.09 (16.02)
Step length variability, cm	2.96 (1.24)	2.64 (0.78)	2.67 (0.96)	2.90(1.00)
DSP variability, ms	22.90 (10.14)	18.94 (5.51)	21.08 (16.62)	24.31 (11.73)
Step width variability, cm	2.07 (0.67)	2.16 (0.75)	2.00 (0.51)	2.18 (0.72)

Notes: SD=standard deviation; DSP = double support phase

Further adjustment for quadriceps strength and reaction time reduced the strength of associations for the average gait measures (Table 8.2). Only greater step length variability (p=0.03) and DSP variability (p=0.02) remained associated with multiple falls in the final model (Table 8.3).

Table 8.2 Adjusted association of average measures of gait with single and multiple falls (n=361):

	No Falls	One fall		Multiple Falls	
	n (%)	n (%)	RR 95% CI	n (%)	RR 95% CI
Speed (cm/sec)					
1st quarter (30.1-102.1)	37 (40.2)	23 (25.0)	1.00	32 (34.8)	1.00
2nd quarter (102.2-116.2)	52 (58.4)	28 (31.5)	1.37 (0.84,2.25)	9 (10.1)	0.34 (0.17,0.69)
3rd quarter (116.3-127.9)	56 (62.2)	23 (25.6)	1.09 (0.63,1.87)	11 (12.2)	0.50 (0.26,0.97)
4th quarter (128.0-180.0)	59 (65.6)	17 (18.9)	0.83 (0.44,1.56)	14 (15.6)	0.80 (0.40,1.61)
P-value for linear trend			0.41		0.27
Cadence (steps/min)					
1st quarter (76.6-103.8)	48 (52.8)	21 (23.1)	1.00	22 (24.2)	1.00
2nd quarter (103.9-110.6)	51 (56.0)	25 (27.5)	1.20 (0.73,1.97)	15 (16.5)	0.64 (0.36,1.12)
3rd quarter (110.7-117.9)	54 (60.7)	27 (30.3)	1.26 (0.76,2.09)	8 (9.0)	0.44 (0.21,0.93)
4th quarter (118.0-139.3)	51 (56.7)	18 (20.0)	0.78 (0.43,1.41)	21 (23.3)	1.13 (0.65,1.97)
P-value for linear trend			0.51		0.96
Step length (cm)					
1st quarter (19.9-56.6)	37 (40.7)	25 (27.5)	1.00	29 (31.9)	1.00
2nd quarter (56.7-62.5)	46 (51.1)	31 (34.4)	1.37 (0.82,2.28)	13 (14.4)	0.63 (0.32, 1.23)
3rd quarter (62.6-68.0)	63 (70.0)	15 (16.7)	0.69 (0.36,1.30)	12 (13.3)	0.58 (0.30,1.13)
4th quarter (68.1-88.8)	58 (64.4)	20 (22.2)	1.01 (0.49,2.05)	12 (13.3)	0.75 (0.33,1.70)
P-value for linear trend			0.31		0.28
DSP (%)					
1st quarter (14.2-20.5)	61 (65.6)	20 (21.5)	1.00	12 (12.9)	1.00
2nd quarter (20.6-22.7)	55 (62.5)	22 (25.0)	1.17 (0.68,2.01)	11 (12.5)	0.80 (0.37,1.71)
3rd quarter (22.8-24.7)	47 (51.1)	21 (22.8)	1.10 (0.62,1.96)	24 (26.1)	1.48 (0.76,2.89)
4th quarter (24.8-40.3)	41 (46.6)	28 (31.8)	1.35 (0.77,2.36)	19 (21.6)	1.31 (0.64,2.67)
P-value for linear trend			0.40		0.19
Step width (cm)					
1st quarter (1.7-8.1)	52 (57.1)	21 (23.1)	1.00	18 (19.8)	1.00
2nd quarter (8.2-9.6)	47 (52.2)	25 (27.8)	1.25 (0.76,2.07)	18 (20.0)	1.07 (0.61,1.88)
3rd quarter (9.7-11.8)	59 (65.6)	22 (24.4)	1.19 (0.68,2.06)	9 (10.0)	0.58 (0.27,1.23)
4th quarter (11.9-21.5)	46 (51.1)	23 (25.6)	1.29 (0.70,2.37)	21 (23.3)	1.17 (0.59,2.29)
P-value for linear trend			0.46		0.99

Notes: Models adjusted for age, height, weight, sex, knee extension strength and reaction time;
RR=relative risk; CI=confidence interval; DSP =Double support phase

Table 8.3 Adjusted association of gait variability measures and single and multiple falls (n=361):

	No falls	Single Falls			Multiple Falls		
	n (%)	n (%)	RR	95% CI	n (%)	RR	95% CI
Step time variability (ms)							
1st quarter (8.81-15.24)	56 (61.5)	20 (22.0)	1.00		15 (16.5)	1.00	
2nd quarter (15.25-18.17)	54 (60.0)	23 (25.6)	1.15(0.68,1.95)		13 (14.4)	0.74(0.38,1.45)	
3rd quarter (18.18-23.77)	52 (57.8)	27 (30.0)	1.28(0.76,2.16)		11 (12.2)	0.59(0.28,1.21)	
4th quarter (23.78-181.85)	42 (46.7)	21 (23.3)	1.03(0.58,1.83)		27 (30.0)	1.21(0.67,2.18)	
P-value for linear trend			0.79			0.40	
Step length variability (cm)							
1st quarter (0.95-2.08)	47 (51.7)	32 (35.2)	1.00		12 (13.2)	1.00	
2nd quarter (2.09-2.53)	56 (62.2)	18 (20.0)	0.57(0.34,0.94)		16 (17.8)	1.44(0.74,2.84)	
3rd quarter (2.54-3.06)	58 (64.4)	20 (22.2)	0.62(0.38,1.02)		12 (13.3)	1.13(0.54,2.38)	
4th quarter (3.07-5.70)	43 (47.8)	91 (25.2)	0.64(0.40,1.04)		26 (28.9)	2.01(1.07,3.80)	
P-value for linear trend			0.08			0.03	
DSP variability (ms)							
1st quarter (5.98-15.19)	63 (69.2)	18 (19.8)	1.00		10 (11.0)	1.00	
2nd quarter (15.20-18.44)	50 (55.6)	28 (31.1)	1.62(0.97,2.71)		12 (13.3)	1.24(0.57,2.67)	
3rd quarter (18.45-23.50)	47 (52.2)	26 (28.9)	1.37(0.81,2.33)		17 (18.9)	1.90(0.93,3.89)	
4th quarter (23.51-169.19)	44 (48.9)	19 (21.1)	0.96(0.53,1.74)		27 (30.0)	2.08(1.06,4.08)	
P-value for linear trend			0.80			0.02	
Step width variability (cm)							
1st quarter (0.80-1.68)	52 (57.1)	22 (24.2)	1.00		17 (18.7)	1.00	
2nd quarter (1.69-2.01)	45 (50.0)	28 (31.1)	1.34(0.83,2.16)		17 (18.9)	0.99(0.55,1.75)	
3rd quarter (2.02-2.44)	52 (57.8)	25 (27.8)	1.09(0.66,1.79)		13 (14.4)	0.75(0.39,1.44)	
4th quarter (2.45-7.04)	55 (61.1)	16 (17.8)	0.71(0.40,1.28)		19 (21.1)	1.15(0.65,2.05)	
P-value for linear trend			0.23			0.83	

Notes: Models adjusted for age, height, weight, sex, knee extension strength and reaction time; RR=relative risk; CI=confidence interval; DSP=Double support phase

Medication use, mood, cognition and other sensorimotor measures were not included in the final models as their addition made little change to the beta coefficients of the gait measures. There were no interactions observed between age or sex and gait measures. When adjusted further for gait speed, both step length variability (p=0.04) and DSP

variability (p=0.04) remained linearly associated with increased risk of multiple falls with little change in the RR values.

Testing for non-linear associations

Tests of quadratic trend were statistically significant for gait speed (p=0.002), cadence (p=0.004), and step time variability (p=0.03) with respect to the risk of multiple falls. When gait speed was dichotomised at 102 cm/sec (the first quartile), the relative risk of multiple falls for those participants with speed ≤ 102 cm/sec was RR=2.11 (1.31-3.42, p=0.002). The ability of this test to correctly classify multiple fallers was then tested in ROC analysis. Without adjusting for covariates, the area under the curve was only 63%, with 47% sensitivity and 80% specificity.

8.5 Discussion

In this prospective population-based study, greater intra-individual variability in step length and DSP were linearly associated with the risk of multiple falls whereas there was a non-linear association for gait speed, cadence and step time variability. These gait measures may be useful clinical measures of the risk of frequent falling in older people, and thus may be good targets for interventions designed to reduce the risk of falls. None of the gait measures were associated with the risk of single falls.

Our study has several strengths. By using a multinomial regression approach, we were able to model for the first time the relative risks of single and multiple falls for several gait measures. It is one of only two prospective population-based studies examining the associations between gait and the risk of falls in both men and women, making the results more generalisable to the wider population than clinic- or volunteer-based studies. The percentage of participants reporting a fall was similar to that found in other prospective population-based studies [8, 9], although higher than in retrospective population-based studies [29, 30]. The prospective recording of falls has the potential effect of minimising recall bias [8]. In addition the follow-up rate was very high with the potential effect of minimising attrition bias. We also carefully examined for non-linear associations and adjusted our analyses for several factors and, importantly in the case of gait variability, also for gait speed.

There are certain limitations to this study. Although we were unable to identify any associations between gait measures and the risk of a single fall, it is possible that we may have found relationships had we measured gait during more challenging tasks. The

response rate at baseline was moderate, but we had a wide distribution of confounders and effect modifiers. Although our follow-up rate was high, loss to follow-up was associated with slower gait speed, shorter step length and greater DSP. This raises the possibility of biased estimates of risk if those lost to follow-up were predominantly non-fallers with slower gait speed, shorter steps or a longer DSP (or fallers with faster speed, longer steps or shorter DSP). The likelihood of such bias is extremely small given the high rate of follow-up. Finally we are unable to generalise these findings to those that are unable to walk without the use of a gait aid.

Poorer performance in gait was not associated with single falls over the one year period. Our results agree with others who have suggested that single falls are less likely to be due to intrinsic impairments that impact on gait patterns [5, 21]. Such falls may be due to factors that have little relationship with gait. These factors include syncope, environmental hazards, and high risk activities that would challenge balance even in a younger person [21, 31]. On the other hand, multiple falls appear more likely to be due to factors that influence gait, particularly those that lead to greater variability in step length and DSP.

It has previously been unclear which gait variability measures best predict future falls. Our results add substantially to the small body of evidence showing that greater variability in DSP and step length increases the risk of any fall [10, 11], and that step time variability is greater in fallers compared with non-fallers [6, 12]. We additionally found that low levels of step time variability also increase the risk of multiple falls, probably indicating that some variability is needed to be flexible and responsive in adapting to perturbations. Our results did not support a previous finding of increased risk of falls in those with either very low or very high levels of step width variability [13]. This may be partly due to the retrospective measurement of falls in that study or to a differing definition of step width [13].

We also identified some unexpected non-linear associations for gait speed and one of its determinants – cadence. There appeared to be a protective effect against falling for speeds greater than 102 cm/sec, a value very close to a cut-off point of 100 cm/sec previously suggested as predictive of falls [9] and other adverse events [32]. Our results indicated that the protective effect was less pronounced for those with gait speeds well in excess of 102 cm/sec. This suggests some older people may walk too fast for their physical ability [33] and thus place themselves at risk. Alternatively those walking at faster speeds may participate in high-risk physical activities that put them at greater risk of falling [21, 31]

These results may be important in informing public health initiatives such as screening gait to predict risk of falling. Gait speed is often considered appealing as it can be quickly and cheaply measured with a stop watch, and a cut-off point has previously been described for predicting future falls in community dwelling older people [9]. However, the predictive performance of gait speed in our study was at best modest, in keeping with findings from a previous study [9]. In our study, using a cut-off point of 102 cm/sec, 53% of multiple fallers would have been missed. Thus, caution may be required when using gait speed as a sole screening test of gait.

However, measuring variability in step length and DSP may provide useful additional information about the risk of falls beyond gait speed in falls-risk assessments. This additional clinical information would provide targets for interventional programs to reduce falls, or to objectively evaluate success of such a program. Further, our results suggest there is no falls-risk reduction benefit of improving gait speed above 102 cm/sec, whereas efforts to reduce step length variability and DSP variability may provide a dose response relationship in reducing the risk of falling.

Possible experimental interventions to reduce gait variability include applying a subsensory vibratory noise to the bottom of the feet whilst walking [34] or pharmacological interventions such as a single dose of methylphenidate [35]. In addition, greater DSP and step length variability are associated with poorer postural stability, slower reaction time, central nervous system impairment and low mood, and these measures may be possible alternate targets for interventions [36-38].

Summary

Greater step length variability and greater DSP variability were linearly associated with increased risk of multiple falls, and gait speed, cadence and step time variability demonstrated non-linear associations. These gait measures could be considered as targets for interventions or as outcome measures in falls prevention programs.

8.6 Postscript

The analyses in the study reported in this chapter show that variability in step length and DSP are associated with increased risk of multiple falls in a dose-response fashion independent of gait speed. Non-linear associations were found for gait speed, cadence and step time variability. These results suggest specific gait measures that may be important as targets for interventions and as outcome measures in falls-risk prevention programs.

The outcomes of the two younger slower women (aged 61 and 62 years) excluded from the analysis of the study described in chapter 4 were reviewed in relation to their gait measures at baseline. Gait measures and falls outcomes for the two women are reported in the table below:

Characteristics of the women excluded from the study reported in chapter 4.

Characteristic	Participant	
	1	2
Age (years)	61	62
Gait speed (cm/sec)	83.0	80.9
Step length (cm)	54.7	47.0
Cadence (steps/min)	91.0	103.3
Step width (cm)	6.08	15.4
DSP (%)	28.4	35.4
Step length variability (cm)	1.69	3.31
Step time variability (ms)	23.01	19.67
Step width variability (cm)	1.58	2.52
DSP variability (ms)	17.63	26.58
Falls	0	0

DSP = double support phase

Although the two women walked at gait speeds of less than 100 cm/sec, and the 62 year old woman's step length variability and DSP variability put her in the quarter of greatest risk of falling, neither woman fell over the 12 month period. This information and the fact that sensitivity of gait speed in predicting falls was modest in the study described in this chapter suggests that the gait measures examined in this study should be used in conjunction with other tests to predict falls in older people.

8.7 References

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Appendix 8A: Characteristics of the overall sample

Table Sample characteristics (n=411)

Characteristic	Overall sample n=411	Included in the analysis of falls n=361
Age, mean (SD)	72.0 (7.0)	72.0 (7.1)
Height in cm, mean (SD)	167.0 (9.0)	166.9 (8.9)
Weight in kg, mean (SD)	77.8 (15.1)	77.5 (14.9)
Medical History (self reported), n (%)		
Arthritis	182 (45)	156 (43)
Hypertension	203 (49)	181 (50)
Diabetes	50 (12)	44 (12)
Stroke	35 (9)	33 (9)
Parkinson's disease	2 (1)	2 (1)
Dementia	2 (1)	2 (1)
Gait measures, mean (SD)		
Gait speed, cm/sec	113.7 (21.3)	114.9 (20.8)
Cadence, steps/min	110.4 (10.1)	110.8 (8.9)
Step length, cm	61.6 (9.3)	62.1 (9.1)
DSP, %	23.2 (3.8)	22.8 (3.7)
Step width, cm	10.0 (2.9)	10.0 (3.0)
Step time variability, ms	22.16 (13.27)	21.99 (13.76)
Step length variability, cm	2.73 (0.93)	2.70 (0.88)
DSP variability, ms	20.08 (10.68)	20.46 (10.73)
Step width variability, cm	2.12 (0.69)	2.12 (0.69)

Notes: SD=standard deviation; DSP = double support phase

Chapter 9: Summary

9.1 Background and aims of the thesis

The ability to walk is important to maintain an independent and active lifestyle. Walking may be affected by disorders that become more prevalent with age [1], often resulting in adverse outcomes such as social isolation, functional dependence and admission to residential care [2]. Importantly, walking impairments can lead to falls resulting in injury, hospitalisation and further loss of mobility [3]. For both the individual and society, the monetary costs associated with falls are large with respect to medical treatments and increased care needs. With the rapid ageing of populations, these costs are likely to continue to rise and may reach unsustainable levels unless they can be prevented. Currently the public health focus is placed on interventions that are implemented after walking impairments or concomitant adverse outcomes such as falls have occurred. There is a clear need to place more focus on programs that prevent, or at least delay, walking impairments in older age. In order to develop such preventive programs, a better understanding is needed of the effect of age on gait, the underlying factors that may influence this association, and the effect of impaired gait on the risk of falls.

Results of previous population-based studies show that gait speed slows with older age [4] due to the combination of age- or disease-related decline in sensorimotor and psychological factors [5, 6]. Very few studies have been performed in population-based samples [5, 7] to investigate age-related changes, or the factors (such as sensorimotor factors) influencing such changes, in other temporal-spatial gait measures (such as step length, cadence, step width and double support phase) and the intra-individual variability of such gait measures. Increased knowledge about the determinants of poorer gait may provide useful targets for clinicians to use in programs to prevent gait decline in older people. Finally, few prospective population-based studies have examined the associations between a wide range of gait measures and the risk of falls in older people [5, 8]. Identification of specific gait measures that increase falls-risk may assist in designing screening tools and simple interventions to prevent this adverse event in older age.

The purpose of this thesis was to examine age-related changes in temporal-spatial gait and gait variability measures, the sensorimotor factors that contribute to gait performance, and associations of gait with falls in population-based samples of community-dwelling persons aged 60-86 years. Specifically the aims of this thesis were to:

1. examine the associations between age, sex and a range of temporal-spatial (a) gait and (b) gait variability measures.
2. examine the associations between a range of sensorimotor factors and temporal-spatial (a) gait and (b) gait variability measures.
3. determine whether poorer performance on a range of temporal-spatial gait and gait variability measures increases the risk of falls.

9.2 Methods

The data from this thesis came from a population-based study (TASCOG) of older people examining associations between brain ageing, gait and falls. The participants were community-dwelling residents of southern Tasmania who were aged 60-86 years and selected in age- and sex- stratified sampling from the Tasmanian electoral roll. Gait measures were collected using the *GaitRite* computerised walkway. Measurements were made of gait speed, step length, cadence, double support phase (DSP) and step width, and of variability in step length, step width, step time and DSP. Sensorimotor factors were measured using the protocols of the Physiological Profile Assessment. They included measurements of quadriceps strength, reaction time, postural sway with the eyes open and eyes closed (on a foam mat), visual contrast sensitivity and proprioception. Falls were measured prospectively over a 12 month period. Participants were asked to complete a falls calendar marking their falls over the period. They were then sent a two monthly questionnaire to complete with information about falls in the intervening period.

9.3 Major findings and implications

Issues in the measurement of the gait parameters (Chapter 3)

Two issues were investigated in this work. The first issue was an investigation of the number of walking trials on a 4.6 metre *GaitRite* mat that are required to provide summary measures that adequately represent the gait parameters. For descriptive studies of gait performance, in which the focus is on mean values, at least six trials were found to be required to represent average measures of gait, and at least four trials were required to obtain an adequate representation of measures of gait variability. For analytical studies of gait, in which the focus is on associations of gait with age and other study factors, three to four trials were shown to be needed to represent average measures of gait, and at least six trials to represent gait variability measures. Overall it was concluded that at least six trials

are needed. This information was available in the studies reported in this thesis because six trials were used in measurement of gait in the TASCOG project.

The second issue concerned the reliability of measurements of gait and gait variability. Assessment of absolute reliability over a one week period demonstrated no significant test-retest differences other than for step width, but the differences in most gait measures were large enough to potentially misclassify ten percent or more of participants in analytical investigations where the continuous gait measures are divided into quarters. Assessment of relative reliability found that ranking of individuals changed markedly for step width variability and DSP variability, but less so for step length variability and step time variability. The ranking of average measures of gait was consistent from week one to week two, as demonstrated by the high values of their ICCs. The results from this study were considered when interpreting the results from the other studies reported in this thesis (see below).

Sex modifies the relationship between age and gait – a population-based study of older adults (Chapter 4)

This is one of the few population-based studies to date to have investigated the associations between age and a range of temporal-spatial gait variables. The key findings were that greater age was associated with poorer performance in a number of temporal-spatial gait measures and that these associations were stronger for older women after the seventh decade of life. With greater age, both men and women walked with slower gait speed, shorter steps, longer DSP and wider step width. In addition, older women also walked with a slower cadence. The results remained largely unchanged after adjusting for self-reported chronic disease suggesting that other age-related factors may be involved.

These age-related gait patterns suggest targets for intervention programs designed to prevent walking impairments in older age. The stronger associations between age and the gait measures among older women suggest particular attention should be given to them when implementing such programs and that screening of gait should begin before the seventh decade. Further, the differences in associations between the sexes suggest preventive programs designed to maintain gait speed should target step length for both sexes and, additionally, cadence for women.

Ageing and gait variability – a population-based study of older people (Chapter 5)

This was the first population-based study to examine the associations between age and both temporal and spatial gait variability measures. Greater age was associated with greater variability in step length, step width, step time and DSP. In addition, gait speed appeared to be an intermediate between age and temporal variability measures, but not between age and spatial variability measures. Similar to the results for the average measures of gait, adjusting for self-reported chronic disease made little difference to the results. Statistically significant associations were found despite the presence of substantial random error in the measurement of the gait variability measures (Chapter 3). In contrast to the results for average measures of gait, only step time variability demonstrated stronger associations among the older women. This may have been due to the intermediate effect of gait speed in this relationship because the associations between age and gait speed were also stronger among older women (Chapter 4). These findings suggest that monitoring of gait variability, and implementation of interventions to prevent increases in gait variability, should occur before the seventh decade of life for both men and women.

A population-based study of sensorimotor factors affecting gait in older people (Chapter 6)

To examine the underlying causes of changes in gait in older age identified in Chapter 4, this study was conducted of the associations between gait and sensorimotor functioning. For both men and women, weaker quadriceps strength was associated with slower gait speed and explained the greatest proportion of variance. These associations were weaker for heavier men and for women with poorer vision. Strength in the quadriceps and other proximal muscle groups (e.g. hip flexors) are important factors in mobility in older people, being susceptible to the effects of deconditioning in frailty. In addition, slower gait speed was associated with slower reaction time for both sexes, greater postural sway (eyes open) for men and poorer proprioception for women with poorer vision. The sensorimotor factors did not fully account for the associations of gait with age, and did not fully explain the stronger associations found between age and gait speed for older women (see Appendix 6B). Results from the pathway analysis of the gait measures in Appendix 6A demonstrated how step length, cadence, DSP and step width and their underlying sensorimotor factors contributed to the associations with gait speed. These findings may assist clinicians in developing more specific interventions to slow the progress of deterioration in gait patterns

in older people. They suggest that preventive programs may be more successful if multi-factorial and sex specific.

Sensorimotor factors affecting gait variability in older people – a population-based study (Chapter 7)

To complete the analyses of changes in gait variability with advancing age, this study was conducted of the associations between gait variability and the sensorimotor factors. Greater postural sway with eyes closed on a foam mat (SEC) was associated with greater variability in step length, step width, step time and DSP. In addition, slower reaction time and poorer proprioception were associated with greater DSP variability and slower reaction time, and weaker quadriceps strength was associated with greater step time variability. Adjusting for sensorimotor factors diminished but did not fully explain the associations of gait variability with age. The associations between sensorimotor function and gait variability may have been stronger had the gait variability measures been measured with less random error (see Chapter 3). Significant associations may have been found with other sensorimotor factors if a larger sample had been used to overcome the attenuation of effect size. In contrast to average measures of gait for which quadriceps strength and reaction time explained the greatest proportion of variance, SEC appeared to be the most important in explaining the gait variability measures, suggesting possibilities for therapeutic interventions to reduce gait variability and associated adverse outcomes. There is some evidence that SEC and other sensorimotor factors may be modified with exercises [9], or compensated for by improving performance in other related ways (by providing a walking stick to aid balance, or by providing advice about footwear to assist those with poor proprioception).

Gait, gait variability and the risk of multiple incident falls in older people- A population-based study (Chapter 8)

This was one of only two population-based studies to examine whether poorer performance on a wide range of temporal-spatial gait variables increases the risk of falls in both older men and women. Over a 12 month period, 25.2% of participants in this sample suffered a single fall and 18.3% suffered multiple falls. The proportion of participants reporting a fall in this study was greater than the proportion reported retrospectively (16.6%) by the same participants in the study described in Chapter 7. Although the reporting of falls was for different time periods, and the increased number of falls reported may reflect a true phenomenon, the difference may also reflect inaccurate retrospective recall of falls.

Poorer gait patterns did not increase the risk of having a single fall, but gait speed and cadence were associated with risk of multiple falls. Despite the much lower test-retest reliability of gait variability measures, greater variability in step length and DSP were associated with the increased risk of multiple falls in a dose response fashion, and there was a non-linear association with step time variability. Associations may have been stronger had gait variability been measured with less error (Chapter 3). The results suggest that these gait measures may be useful as targets for interventions to reduce risk of multiple falls. In addition, the average gait measures that were measured with high test-retest reliability could be used as intermediate outcome indicators in falls prevention programs. Taken together, these results and those from Chapters 6 and 7 suggest a number of sensorimotor factors that may be useful as therapeutic targets to improve performance in gait thereby reducing the risk of falling in older people.

Strategies to reduce falls in older people

The studies reported in this thesis have identified gait (Chapter 4 and Appendix 6A) and sensorimotor factors (Chapters 6 and 7) that could be assessed for efficacy in intervention programs to improve gait performance and reduce the risk of falls.

Targets for interventions to maintain gait speed and cadence

Gait speed and cadence (a determinant of gait speed) were associated with increased risk of multiple falls. The results reported in this thesis suggest three methods by which deterioration in these gait measures may be minimised in order to reduce falls-risk in older age.

Firstly, gait speed could be maintained by encouraging people to maintain step length and cadence (the determinants of gait speed). The differences in associations reported in Chapter 4 for men and women suggest that in order to maintain sufficient walking speed, both sexes should concentrate on maintaining step length and, in addition, women should also focus on maintaining cadence. Secondly, if speed is unable to be maintained in this way, perhaps because slower gait speed is used as a compensatory mechanism for poor balance, sensorimotor factors associated with faster gait speed could be targeted in interventions to improve sensorimotor function. The improvements required include improved quadriceps strength and reaction time for both sexes, reduced postural sway and body weight for men, and reduced effect of deficits in vision and proprioception for women (Chapter 6). Thirdly, if deficits in a particular gait measure (step length, cadence, DSP or step width) are contributing to the difficulty in maintaining gait speed, and that gait

measure can be identified (using relatively simple methods such as a stopwatch and measured walkway or more sophisticated methods such as a computerised walkway), specific sensorimotor interventions can be focused on the impaired gait measure. For example, attempts to maintain cadence could be made by targeting reaction time, with the addition of measures to improve quadriceps strength for women (Chapter 6 and Appendix 6A).

Targets for interventions to maintain gait variability

Greater variability in DSP and in step length were associated with multiple falls in a dose-response fashion, whereas the association with step time variability was more complex and non-linear. Our findings suggest that interventions to reduce postural sway may be an effective method of preventing an increase in variability in these gait measures. Other targets for interventions include reducing the effects of slower reaction time and poorer proprioception to further maintain or reduce levels of DSP variability, and improving quadriceps strength and reaction time to further maintain or reduce step time variability.

What types of interventions could be used?

Interventions to improve step length and cadence could be as simple as practicing taking bigger steps or walking with a faster metronome-guided rhythm on the ground or on a treadmill. Interventions to improve sensorimotor function could include exercise programs designed to improve quadriceps strength, postural stability and reaction time and to reduce body weight. Alternative interventions may include advice on the best footwear to compensate for poor proprioception, tape on areas of low contrast (such as stairs) for those with poor visual contrast sensitivity, dietary advice for those overweight, and the provision of a gait aid to improve postural stability when walking.

At what age should screening and preventive programs be implemented?

The associations between older age and slower gait speed, slower cadence and greater variability in step length, DSP and step time in these samples of 60-86 year old community-dwelling people suggest that falls-risk screening and preventive programs should be implemented or offered in the community for those as young as sixty years of age (Chapters 4 and 5). There may be benefit in providing them for people younger than sixty years of age, but confirming this would require further investigations in people younger than those in the studies reported in this thesis.

9.4 Recommendations for future research and needs

The studies in this thesis have provided new and additional information on how a wide range of gait measures are associated with advancing age and sensorimotor function. In addition, specific gait variables that are associated with risk of multiple falls have been identified as targets for intervention. There are some unanswered questions, and the findings have prompted other issues. These are summarised below:

- Advances in technology are required to improve the accuracy of measuring some gait parameters. The *GaitRite* computerised walkway may not be able to measure spatial gait variables of small magnitude (such as step width) with sufficient precision. This may explain the significant difference found for step width over a one week period in the test-retest study (Chapter 3). Improved or alternate technology may result in measurements that are more sensitive and able to detect smaller changes than those detected at present [10].
- The results from the study in Chapter 3 suggest that the walking speed of participants increased as they became more familiar with the walking test. This was despite having two practice trials. It is possible that the initial walk in an unfamiliar environment may be a better indicator of risk of falls than are the summary measures from multiple walks when the participant has become practised and more confident. A limitation of the study reported in Chapter 8 was that data was not collected on the first practice trial.
- The results from chapters 4-7 examining the associations between gait, age, and sensorimotor function were cross-sectional. The causal nature of these associations needs to be confirmed in longitudinal studies. Furthermore the results from chapters 6 and 7 suggested that a number of sensorimotor factors may be useful as targets in intervention programs to improve age-related gait patterns and reduce falls. If these findings are replicated in other cross-sectional studies or ideally in longitudinal studies, randomised control trials of sufficient size will be required to confirm the feasibility and efficacy of the designed interventions.
- Future studies need to investigate the roles of other potentially contributing factors such as strength in other muscle groups, muscle power, dynamic balance, joint range of movement, cognitive function, mood and pain. The proportion of the variance explained by the sensorimotor measures for each gait measure was limited, particularly for the gait variability measures. Furthermore, poorer

performance in sensorimotor function did not explain the stronger associations between age and gait speed found in older women.

- In the studies of this thesis, testing of gait measures occurred over a flat surface without any distractions. Future studies should examine whether stronger or different associations between gait measures and age, sensorimotor function and falls may be found if a more difficult 'real life' (such as a dual task or walking over rough ground) walking task was used. Furthermore it may be informative to include the commonly used Timed Up and Go test [11] to determine its ability to predict multiple fallers, and to compare the results with those of the measures used in this study.
- Further research is needed to determine whether other factors are able to predict risk of having a single fall. Poorer performance in the gait measures was not associated with risk of a single fall in a one year period. Single falls may also result in adverse events such as fractures and hospitalisation, and these people may go on to fall more frequently.
- Finally, results from studies in this thesis suggest that, in order to prevent deterioration in gait patterns and the occurrence of falls, older people should adopt exercises to improve sensorimotor function such as muscle strength, balance and reaction time. However there are a number of possible barriers to adopting such programs. More research is needed to investigate how best to facilitate and encourage people to exercise. Furthermore, governments need to provide affordable, safe and access friendly environments to encourage participation in such activities by older people.

9.5 Conclusion

The carefully designed sequence of population-based studies presented in this thesis provided an avenue for important and new information about changes in gait patterns with advancing age, their underlying sensorimotor mechanisms, and the contribution of gait disorders to risk of falls. The results identify specific gait and sensorimotor factors that can be targeted in programs to prevent walking decline and falls in community-dwelling older people.

The following conclusions are made with reference to the initial study aims:

1. (a) Advancing age was associated with slower gait speeds, shorter steps, a longer DSP and wider step width in both sexes with the addition of a slower cadence in women. Stronger associations between age and all gait measures were found among women of greater age.
   (b) Advancing age was associated in a dose-response fashion with greater variability in step length, DSP and step width. For step time variability, stronger associations were found for older women. Gait speed may mediate the association between age and temporal (step time and DSP) gait variability measures.

2. (a) Reduced performance in quadriceps strength, reaction time, sway on a foam mat (eyes open and eyes closed), visual contrast sensitivity and proprioception was associated with poorer performance in average measures of gait. The associations differed between the sexes. Quadriceps strength explained the greatest proportion of the variance for most measures.
   (b) Greater SEC was associated with greater variability in all gait measures. Slower reaction time was associated with greater variability in both temporal (DSP and step time) measures whereas poorer proprioception was associated with greater DSP variability and weaker quadriceps strength was associated with greater step time variability. Other sensorimotor factors were not independently associated with gait variability. SEC explained the greatest proportion of the variance.

3. Gait speed and cadence were non-linearly associated with multiple falls. Of the gait variability measures, greater intra-individual variability in step length and double support phase were associated with increased risk of multiple falls in a dose-response fashion, and there was a non-linear association with step time. None of the gait measures predicted single falls.

9.6 References

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